

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**UPPER ATMOSPHERIC JOULE HEATING AND MAGNETOSPHERIC
SUBSTORMS: A CASE STUDY**

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Department : Meteorological Engineering

Programme : Atmospheric Sciences

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**YUKARI ATMOSFERDE JOULE ISINMASI VE MANYETOSFERİK
MİKROFIRTINALAR:BİR VAKA ANALİZİ**

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ŞUBAT 2010

FOREWORD

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Atmospheric Sciences Programme

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ABBREVIATIONS

AE	: Auroral Electrojet Index
ASI	: All Sky Imaging Array
BATSRUS	: Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme
B, B_x, B_y, B_z	: Magnetic field magnitude, Magnetic field x,y,z component
CCMC	: Community Coordinated Modelling Center
CD	: Current Disruption
Dst	: Disturbance Storm Time Index
ε	: Akasofu's Epsilon Parameter
FGM	: Fluxgate Magnetometer
GAKO	: Gakona
IMAGE	: International Monitor for Auroral Geomagnetic Changes
IMF	: Interplanetary Magnetic Field
J	: Ionospheric current
JH	: Joule Heating
Kp	: 'Kennziffer' Planetary Index
MCGR	: McGrath
MHD	: Magnetohydrodynamics
MIRACLE	: Magnetometers-Ionospheric Radars-All-sky Cameras Large Experiment
MOM	: Electrostatic Analyzer On board Moments
NENL	: Near Earth Neutral Line
n	: Number density of the solar wind
SuperDARN	: Super Dual Auroral Radar Network
SWMF	: Space Weather Modelling Framework
Σ_H	: Height integrated Hall conductivity
σ_H	: Hall conductivity
Σ_P	: Height integrated Pedersen conductivity
σ_P	: Pedersen conductivity
THEMIS, Th	: Time History of Events and Macroscale Interactions during Substorms
Ua	: Auroral Particle Precipitation
UT	: Universal Time
V_{sw}	: Velocity of the Solar Wind
V_x, V_y, V_z	: X, Y, Z component of velocity
WHIT	: White Horse

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UPPER ATMOSPHERIC JOULE HEATING AND MAGNETOSPHERIC SUBSTORMS: A CASE STUDY

SUMMARY

Space weather, by definition, is the conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life or health (ESA). Increasing critical needs of human society on the technology based applications demand reliable predictions of the near Earth space environment. More specifically the electricity depended technology crucially need improved space weather predictions (Siscoe, 2007). During geomagnetic storms and magnetospheric substorms, electrical and magnetic changes in both ground level and Near Earth Space are observed affecting the spacecraft instrument's functions. On the ground level, disturbance-time currents, called Geomagnetically Induced Currents (GICs), affect pipelines and electrical systems, depending on the degree of the activity, causing large blackouts in wide regions as in the case of October, 2003 geomagnetic storm in Northeast USA. In near Earth space, incoming solar and cosmic particles to Earth's magnetospheric system and filling the radiation belts, which are accelerated and energized during the substorms, may damage satellites as well as prevent the radio communications. Additionally, the increased atmospheric drag due to the upper atmospheric heating leads to shorter satellite lifetimes. In major geomagnetic storms, some of the satellites can also be lost.

The space studies speeded up especially after 1950s when first rocket measurements of Van Allen radiation belts have been carried out. The improved technology on computers and advancements in satellite technology, thus increasing observations of space environment allow scientist to study and model the Earth's near space environment and increase our knowledge of understanding of this huge dynamic system and the physics behind how it works. As a crucial part of the system, magnetic storms and magnetospheric substorms are the means of transferring energy and momentum from the solar wind into the upper atmospheric system and thus is important to understand its dynamics in all temporal and spatial scales.

This study includes the estimation of energy input from the solar wind to magnetosphere and three different approaches for upper atmospheric Joule heating dissipation during substorms. One approach uses statistical analysis and local and global auroral indices derived from long statistical studies to determine the joule heating. Second approach uses the magnetohydrodynamics theory based simulations which are in continuous improvements. Third approach combines the conductivity models (IRI2007) and electric field measurements of SuperDARN radar.

Three magnetospheric substorm cases were selected and studied extensively. Here, we present one, which consists of two consecutive substorm periods. The cases were chosen according to the substorm criteria and auroral activations observed on Earth at high latitudes. General characteristics and signatures of substorms were presented and analyzed. Within the context, magnetotail flows and their associated consequences on the upper atmosphere corresponding to our substorm event were investigated. The main purpose of the study was to derive the energy budget and make comparisons between the model estimations and statistically derived estimations of joule heating in the upper atmosphere and address the changes in the tail dynamics and ionosphere that led to the differences in joule heating calculations.

We can compare the differences in three categories: the magnitude of the peak joule heating, the timing of the peak joule heating and the trends during the course of the substorm development. We find that AE index based method gives the highest joule heating rates. This has been compared with the IL index based computations as well where we see the lowest values due to the limited spatial coverage of this local index. The simulation results of joule heating rates are comparable with those obtained by AE based method. However, we see that the peak time of the joule heating rate occurs about half an hour earlier than that of AE index. The joule heating rates from SuperDARN electric field with IRI2007 conductivity are found to be closer to those of AE index based method during the first substorm. However, it gave an overestimated joule heating rate, an order of magnitude larger, during the second substorm which could be attributable to the tail dynamics. These discrepancies will be discussed in the discussion section of the thesis.

In chapter 1, the concepts of geomagnetic storms and substorms are introduced to the reader, and a literature search about the upper atmospheric Joule heating is given. Chapter 2 covers the magnetospheric and ionospheric models used throughout the study while Chapter 3 includes the data sources used. Results are presented in Chapter 4, and discussion and summary of the results are given in Chapter 5. The reader can also find the future work in the conclusion section of Chapter 5.

YUKARI ATMOSFERDE JOULE ISINMASI VE MANYETOSFERİK MİKROFIRTINALAR: BİR VAKA ANALİZİ

ÖZET

Uzay havası, Avrupa Uzay Ajansının yapmış olduğu tanıma göre Güneş ile Dünya arasındaki ortamda meydana gelen değişimleri belirlemeyi ve bunların tahminini içerir. İnsan aktivitelerinin giderek hızla artan bir şekilde elektriğe dayalı teknolojilere bağımlı olması uzay havası tahminlerini ve bu tahminlerin mümkün olduğunca tutarlı olmasını gerektirmektedir. Manyetik fırtınalar ve manyetosferik mikrofırtınalar esnasında hem yer seviyesinde hem uzay ortamındaki faaliyetleri etkileyebilen değişiklikler gözlenmektedir. Yer seviyesinde, elektrik sistemleri ve petrol boru hatları bunların en direk gözlenebilir etkileridir. Ekim 2003'de meydana gelen bir manyetik fırtına nedeniyle Kuzeydoğu Amerika'da görülen uzun süreli elektrik kesintisi bunun en son örneğidir. Manyetik fırtınalar esnasında yer yüzeyinde saptanan jeomanyetik olarak indüklenmiş elektrik akımları bunun temel nedenidir. Yere yakın uzay ortamında ise, manyetik ve manyetosferik fırtınalar esnasında enerji seviyeleri yükseltilmiş ve hızlandırılmış güneş rüzgarı ve kozmik parçacıklarla dolan radyasyon kuşakları uydular için çok büyük tehlikeler oluşturmaktadır. Uydular bu bölgelerden veya civarından geçerken elektrik yüklenmesi, hassas aletlerin fonksiyonlarının kaybedilmesi, yer istasyonu ile olan iletişimi sağlayan aletlerinin bozulması vb gibi uyduların irtifa kaybetmelerine kadar uzanan bir sürü zarara maruz kalırlar. Çok kuvvetli manyetik fırtınalar esnasında bazı uydular tamamen kaybedilebilir.

1950lerde roket ölçümleri ile başlayan manyetosferik ölçümlerin getirdiği gelişmeler, bunu takiben giderek büyük bir hızla artan bilgisayar ve uydu teknolojilerinde meydana gelen gelişmeler ve artan uzay uydusu gözlemleri manyetosfer gibi boyutları (100Rex30Re) devasa bir sistemin hem zamansal hem de uzaysal açıdan incelenmesini ve modellemesini mümkün hale getirmiş ve sistemin arkasındaki fizik ve dinamik olayları anlamamıza olanak vermiştir. Manyetik ve manyetosferik fırtınalar bu dinamik sistemin güneş rüzgarı-manyetosfer-iyonosfer arasındaki enerji ve momentum transferini sağlayan en kompleks mekanizmalardır. Her ne kadar uydu gözlemleri, manyetosferik sistemin global boyutu ve değişimleri hakkında yeterince inceleme imkanı tanımış olsa da, manyetik ve manyetosferik fırtınaların temporal ve uzaysal gelişiminin çok lokal olması ve çok boyutluluğu olayların karmaşıklığını artırdığından halen uydu gözlemleri ile yeterince çözümlenememişlerdir.

Bu tez çalışması, seçilen manyetosferik fırtına günlerinde güneş rüzgarından manyetosfere aktarılan enerji miktarını hesaplamayı ve bunun sonucunda yukarı atmosferde meydana gelen Joule ısınmasının hesaplanması için üç farklı yaklaşımın karşılaştırılmasını kapsar. Birinci yaklaşım Joule ısınmasını istatistiksel olarak oluşturulmuş kutup ışıkları (aurora) indeksini (AE) kullanarak hesaplamayı içerir. İkinci yaklaşım manyetohidrodinamik teoriyi kullanan BATSRUS model verilerini kullanır. Üçüncü yaklaşım ise SuperDARN radarının elektrik alanı ölçümleri ile IRI2007 iletkenliklerini kullanmaktadır.

Çalışmamıza temel olacak vakalar seçilirken, yukarı enlemlerde gözlemlenen kuzey ışıkları spektrumları ve yer manyetik alan verilerinde mikrofırtına kriterleri incelenmiştir. Bu incelemeler sonucunda 3 adet manyetosferik fırtına olayı tesbit edilmiştir. Bu üç olay esnasında manyetosferde, iyonosferde ve yerde gözlemlenen değişiklikler Joule ısınması sırasında bu ortamlardaki fiziksel ve dinamik olayların anlaşılmasına yönelik olarak detaylı olarak incelenmiştir. Ancak çalışmanın çok yüklü olması nedeni ile tez çalışmamızda sadece bir tanesi teferruatlı olarak sunulmuştur. Diğerleri tez çalışmamıza dayanan makalemizde verilecektir. Tezde detayı verilmek üzere seçilen manyetosferik mikrofırtına vakası birbiri arkasından oluşan iki ayrı mikrofırtınayı içermektedir. Çalışmamızda genel olarak mikrofırtınaların özellikleri analiz edilmiştir. Yukarı atmosferde meydana gelen Joule ısınması yukarıda bahsedilen üç metod ile hesaplanmış, sonuçlar karşılaştırılmış ve farklılıklar ortaya konulmuştur. Bu farklılıkların nedenleri iyonosferde ve manyetik kuyrukda mikrofırtınalar esnasında meydana gelen fiziksel ve dinamik süreçler bağlamında tartışılmıştır.

Üç yöntem ile hesaplanan Joule ısınması sonuçlarında görülen farklılıklar üç grupta toplanabilir: 1. Maksimum joule ısınması değerleri, 2. Maksimum joule ısınmasının meydana geldiği zaman, 3. Tüm mikrofırtına sürecinde joule ısınmasının gidişatı (trend). AE indeksi kullanarak hesaplanan Joule ısınması değerlerinin en yüksek değerler olduğu görülmüştür. IL hesaplamaları, bu indis lokal bir indis olduğundan, bütün yöntemlerden daha düşük joule ısınması değerleri vermiştir. Manyetohidrodinamik BATSRUS modelinin simülasyon sonuçları ise AE ile aynı mertebede joule ısınması sonuçları vermiştir. Ancak simülasyon sonuçlarında maksimum ısınma zamanının, AE ile hesaplanan maksimum ısınma zamanından yaklaşık yarım saat önce olduğu belirlenmiştir. SuperDARN radarının elektrik verileri ve IRI2007 iletkenlikleri kullanılarak hesaplanan joule ısınması ilk fırtına sırasında AE ve BATSRUS model sonuçları ile mertebe olarak uyumlu bulunmuştur. Ancak ikinci fırtına esnasında bir mertebe yüksek joule ısınması elde edilmiştir. Bunun farklılıkların nedenleri manyetik kuyruk verileri ile ilişkilendirilerek kuyruk dinamiği ile tartışılmaktadır.

Tezin birinci bölümünde, manyetik fırtına ve mikrofırtına kavramları okuyucuya tanıtılmıştır. Yukarı atmosferde Joule ısınması hakkında bir literatür taraması verilmiştir. Bölüm 2 çalışmamız esnasında kullanılan iyonosferik ve manyetosferik modelleri kapsarken, Bölüm 3 analizlerimizde kullanılan veri kaynaklarını içermektedir. Analiz ve elde edilen sonuçlar Bölüm 4’de sunulmuştur. Sonuçların tartışması ve çalışmamızın özeti ise Bölüm 5’de verilmektedir. Okuyucu bu çalışmanın geliştirilmesine yönelik önerileri de bu bölümde bulabilir.

1. INTRODUCTION

The Sun, in the center of the Solar System, affects the planets and everything around itself by its continuous supersonic plasma ejection which is called the solar wind and reaches the Heliopause; a boundary separating interplanetary medium and the solar wind, at which stellar winds alter the strength of the solar wind. The Earth confronts the effects of the Sun by its own magnetosphere, the cavity region formed owing to its internal magnetic field (Baumjohann et al., 1996, Chian et al., 2007).

The magnetosphere has an essential role in the initiation and continuation of life on Earth. Without it, probably no life could have ever occurred on Earth because of the intense flux of particles coming from the Sun. With our improving technology, it is also essential to know the physics and how processes happen in magnetosphere as satellite systems in space and communication systems on Earth as well as the long-distance pipelines, electric transformer systems, and astronauts on spacecraft are being affected by the solar-wind conditions (Siscoe, 2007).

The first event ever linked with the solar condition changes and the changes on Earth was the Carrington event observed in September 1, 1859 by Sir Carrington while he was observing the sunspots. He had seen a flare (sudden brightness increase) on the Sun having a complex sunspot region as a source, which is nowadays, classified as an intense X17 white light flare. Following his observation, the telegraph system failure, cable discharges, and auroral displays in various places especially in the high latitudes led Sir Carrington to suspect the main cause was a flare he had seen (Akasofu, 2002).

In general, aurorae or the so-called northern lights are the only visible signatures of the energy deposition to Earth's ionosphere and upper atmosphere while changes are also observed in the Earth's magnetic field, ionospheric electric field and conductivities detected at the ground instruments such as the magnetometers, ionosondes and ground radars (Tanskanen, 2002). The disturbances observed on the ground level have direct links with the modifications of the magnetospheric environment by the solar wind owing to the fact that there is strong coupling between the magnetospheric and ionospheric currents as magnetosphere can be thought as a closed circuit (Ridley et al., 2004). The event that Carrington observed was also associated with a major geomagnetic storm (Akasofu, 2002).

Several processes may come into play during disturbed solar wind conditions. Solar wind dynamic pressure may become enhanced pushing the magnetopause earthward thus shrinking the magnetic field on the dayside, and stretching it on the nightside hence causing the currents in the system to change, or periods of strong southward interplanetary magnetic field z component may be seen leading to magnetic reconnection in dayside and nightside regions of the magnetosphere. The latter would cause the greater amount of particles entering the Earth's atmosphere, and strengthen the convection in ionosphere in addition to the disturbance time ionospheric currents (Tanskanen, 2002, Chian et al., 2007).

Classifications of the disturbances observed on Earth have been done to enlighten the major processes in charge to understand the mechanisms. A global change in magnetic field was termed as a geomagnetic storm, whereas a substorm was defined as a short-lived process during which energy was deposited into auroral ionosphere and magnetosphere having its sources in the magnetotail region (Rostoker et al., 1980).

1.1 Purpose of the Thesis

The purpose of this thesis is to make comparisons between the various methods of calculating Joule Heating using MHD based simulations, index-based statistical methods, and calculations from direct electric field measurements combined with conductivity models in the transfer of stored solar wind energy particularly to the ionosphere during substorms.

For this purpose, first, three cases were selected and analyses of substorm characteristics were performed such as the phase determination of the substorms and solar wind drivers of the activation.

Following this, the energy input to the magnetosphere was estimated using Akasofu's epsilon parameter, and output in the ionosphere by means of Joule Heating and auroral particle precipitation contributions, using the relations that are given in the Ostgaard, 2002 article which are based on geomagnetic indices. Tanskanen's method which is based on another geomagnetic index using a different magnetometer chain was also used.

The corresponding changes in magnetotail region were also investigated for each case by using THEMIS mission satellites for the purpose of identifying the physical and dynamical causes of the changes in the joule heating rates which will be briefly explained in the following chapters.

To make the comparisons, a global magnetosphere model was run for the cases using the CCMC (<http://ccmc.gsfc.nasa.gov/>) web interface, giving the solar wind parameters as input to the selected model: SWMF/BATSRUS.

Also, Joule heating was calculated in a third way, using the relationship between parallel flowing currents and the electric field. Pedersen conductivities were taken from International Reference Ionosphere Model 2007 (IRI2007), while electric field values were taken from SuperDARN radar network.

In the following sections, a brief introduction to magnetospheric environment, geomagnetic storms, substorms and recent studies about the energy budget will be given. Models used in this study will be shortly explained, and the results will be introduced with discussions and the conclusions.

1.2 Magnetospheric Environment

The magnetosphere of Earth is a separate region surrounded by the solar wind flow in which the magnetic field of Earth dominates. The impinging solar wind causes Earth's magnetic field to be pushed from the dayside, and to get stretched on the nightside. Hence, the magnetotail is created. The boundary separating the both environments that of solar wind and that Earth's magnetic field dominates is the magnetopause boundary. At this boundary the solar wind dynamic pressure is equal to the magnetic pressure of the Earth. The plasma ejected from the Sun first meet the bow shock at which the supersonic flow of the solar wind is reduced to subsonic flow, and squeezed and became turbulent between magnetopause and the bow shock. This region of shocked solar wind is called the magnetosheath.

The continuously moving charged particles in Earth's magnetosphere create currents in the magnetospheric environment that ultimately close in the ionosphere via the field aligned currents (FACs), and all of this system is affected by the solar wind conditions.

Average solar wind contains 3 to 6 atoms per cubic centimeters of $1.4-1.6 \times 10^5$ K temperature and has a dynamic pressure about 1.2 nPa coming with 400 km/sec velocity (Parker, 2007).

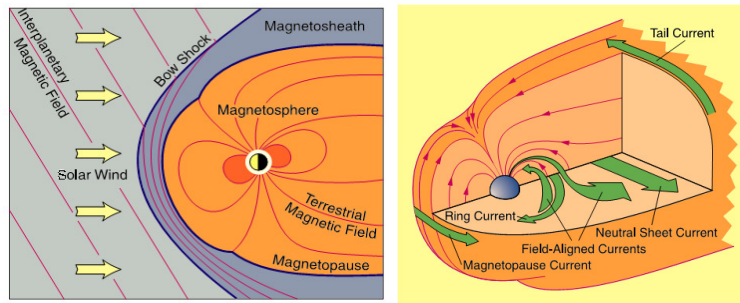


Figure 1.1: Magnetospheric Environment (Vogt, 2004)

In Figure 1.1 the currents and regions formed due to the processes mentioned above are seen. On the dayside, the dayside magnetopause current flows because of the necessity of balance between magnetic field of Earth and solar wind dynamic pressure.

This current system is pushed towards Earth during solar wind periods of high density and/or velocity when dynamic pressure is enhanced, and creates positive

fluctuations in Earth's magnetic field because of its direction. In the nightside the cross-tail current system is seen, in addition to the ring current around Earth flowing in westward direction due to the drift of particles. Magnetospheric convection controls the number density of particles in that region. The current is closed in both field aligned currents through ionospheric currents or in magnetosphere. Ring current is stronger in the night side of the Earth and it's not uniform (McPherron, 1991).

1.3 Geomagnetic Storms and Magnetospheric Substorms

During geomagnetic storms and magnetospheric substorms the current systems in the magnetosphere undergo some changes. In Table 1.3 the processes that occur in the magnetospheric system are summarized and differences between geomagnetic storms and magnetospheric substorms are indicated.

Table 1.1: Geomagnetic Storms and Substorms

Geomagnetic storms	Substorms
• Strong narrowing and compression of magnetosphere • Ring current induction • Aurora visible at lower latitudes • Lasts for several days • Consists of initial, main and recovery phases. • Horizontal magnetic field's decrease • Filling of radiation belts with energetic particles • Dst decreases • Dst, Kp, AE, AU, AL are a good measure of a geomagnetic storm.	• Two mechanisms suggested: directly driven and loading unloading method • Nightside and dayside reconnection can trigger the substorm process • Southward IMF • Transport of magnetic flux from dayside to tail • Storage in tail during growth phase • Rapid release of energy • Fast flows in magnetotail • Plasma ejection in tailward direction • Energetic particle injections at geosynchronous distances • Field-aligned systems strong intensification • AU and AL describes well. • Loss of energy from the ring current

Substorms differ from geomagnetic storms in both spatial and temporal scale. They are ubiquitous in nature and may also occur during solar minimum. As a result, they have proven to be valuable tools in understanding the nature of energy transport and conversion mechanisms.

The transport of energy may be in two ways in substorms: loading-unloading and directly driven. Directly driven process includes the direct response of magnetosphere to the impinging solar wind whereas during loading-unloading process there is first the energy storage in magnetotail and release after some threshold value (McPherron, 1991).

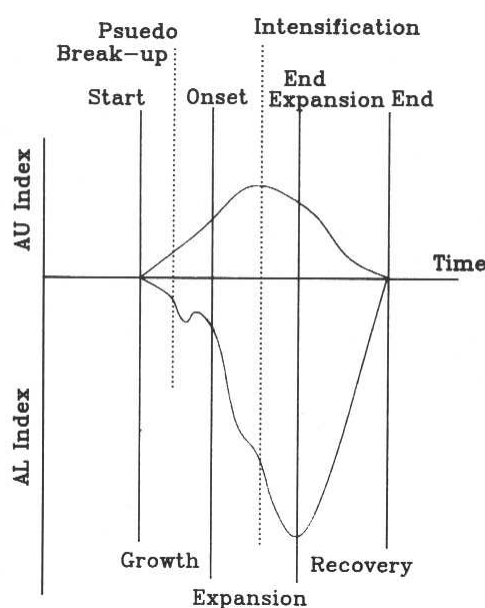


Figure 1.2: Substorm phases with respect to AU and AL indices (McPherron, 1991)

A substorm has typically onset, growth, expansion and recovery phases which are shown in Figure 1.2. During the growth phase an equatorward expansion and brightening of the auroral arc is seen as well as the stretching of magnetotail, while the onset auroral break-ups to multiple microstructures are observed. Onset is the time that stored energy in magnetotail during the growth phase starts to get released causing the expansion phase during which east, west and poleward movements of auroras are noticed. The situation starts to get to its initial values with recovery phase which is the last stage of the substorm (Donovan et al., 2006).

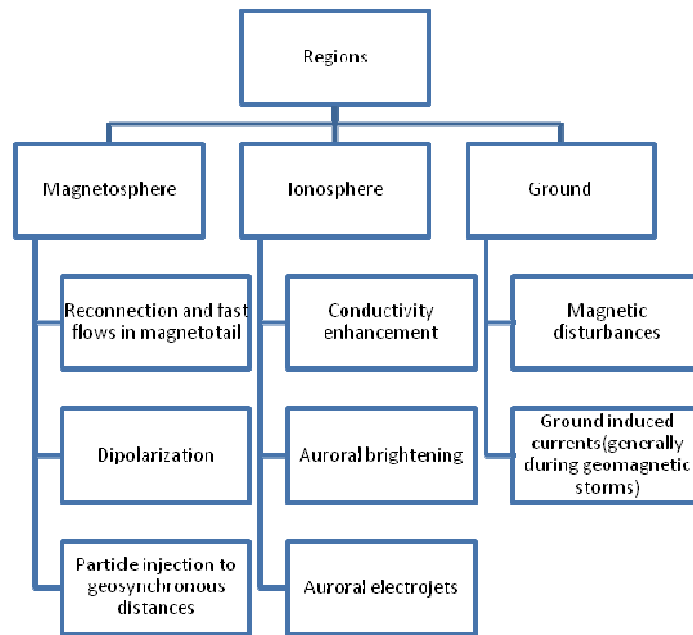


Figure 1.3: Substorm signatures according to the region

The signatures of substorms can be observed in magnetosphere, ionosphere and on the ground. In magnetosphere, reconnection and fast flows in magnetotail, dipolarization of the field lines, and particle injection to geosynchronous distances are observed as well as the conductivity enhancement, auroral brightening and auroral electrojets in the ionosphere. The ground signatures are usually from the measured geomagnetic field values, however during strong geomagnetic storm time substorms ground induced currents may also be observed. Figure 1.3 summarizes all the signatures observed in these regions.

Recent debates about substorm theory have been on the time sequence of events. Among the leading substorm theories Current Disruption and Near Earth Neutral Line model are the most supported ones due to the observational proof. Both theories put forth the same events basically: reconnection in the tail, current disruption in near Earth region and formation of auroras in the ionosphere. Though, as seen in Figure 1.4, current disruption model suggests the current disruption as the mechanism causing the rarefaction wave and the occurrence of reconnection in tail afterwards, in the end leading to auroras, and in contrary to CD, NENL model depends on reconnection as the initial disturbance. According to the NENL model, first reconnection causes the current disruption to occur, then particles are transported both Earthwards and tailwards creating aurorae (Lui, 2003).

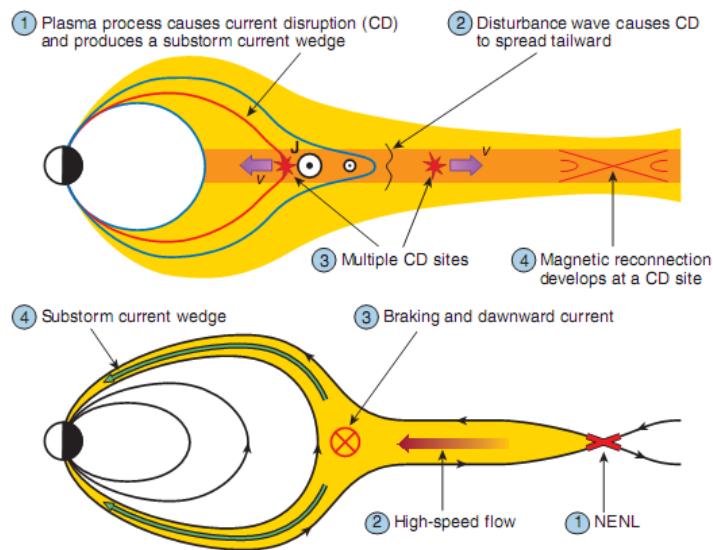


Figure 1.4: Schematics for CD and NENL Models (Lui, 2007)

1.4 On the Energy Budget of Substorms: Literature Search

According to Akasofu, with the discovery of the relationship between the southward turning of the interplanetary magnetic field z component and geomagnetic disturbances by Donald Fairfield in 1967 and the magnetic reconnection theory of Dungey (1971), a new insight for the energy transfer mechanisms from the solar wind to the magnetosphere arose (2002).

The theories widely used today basically rely on the fact that solar wind transfers energy and momentum to Earth's magnetosphere as it interacts with the magnetopause boundary. At the time of the interaction, the energy deposited dissipates in several channels. For geomagnetic storms, the main dissipation channels are the ring current, joule heating, auroral particle precipitation, and plasmoid release (Koskinen, 2002).

In his study magnetospheric energy budget and the Epsilon Parameter, Koskinen argues about the physical meaning and correct interpretation of the epsilon parameter which is a common tool for the computation of input energy during substorms and geomagnetic storms. He points out that epsilon parameter is actually a transfer function and it cannot be considered as an energy source. The energy flow related with the solar wind is much larger besides the transferred energy amount dependent on the kinetic energy-magnetic energy conversion which is by means of reconnection.

Epsilon parameter includes the solar wind and dimensional parameters in its formulation; solar wind speed, V , the square of the magnetic field magnitude B , IMF clock angle which gives the orientation of the IMF, θ (eq. 1.2), and a factor for the physical dimension of length, l_0^2 as seen in equation 1.1.

$$\varepsilon = \frac{4\pi}{\mu_0} v B^2 \sin^4\left(\frac{\theta}{2}\right) l_0^2 \quad (1.1)$$

$$\theta = \tan^{-1} \frac{B_Y}{B_Z} \quad (1.2)$$

For the dissipation of energy much work has been done using various methods.

In Figure 1.5 the dissipation regions are shown by a sketch of Tanskanen. Blue arrow represents the Joule Heating, while the green one represents the auroral particle precipitation and the red arrow represents the ring current. In addition, there is the plasmoid release in the magnetotail shown in brown.

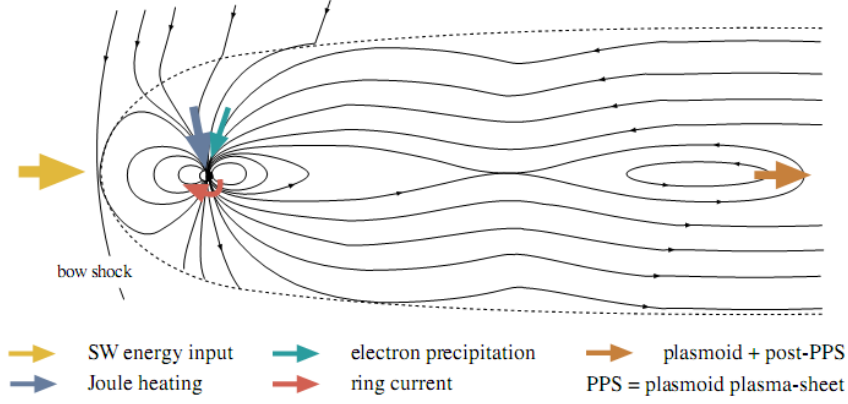


Figure 1.5: Energy sinks and sources in the magnetosphere (Tanskanen, 2002)

Among those, Joule heating is the ohmic heating produced by currents flowing in parallel direction of electric field (Palmroth, 2003), and auroral particle precipitation is the heating produced due to the collisions of precipitating electrons with neutrals in ionosphere.

As Joule Heating is only produced by currents flowing parallel to the electric field its rate can be written as

As Joule heating is only produced by currents flowing parallel to the electric field the rate of it can be written as

$$Q_j = J_{\text{perp}} \cdot E_{\text{perp}} \quad (1.3)$$

Since the only contribution comes from the Pedersen currents flowing parallel to the electric field in the ionosphere, height integrated Joule heating in equation 1.3 becomes

$$Q_j = \Sigma_p \cdot E_{\text{perp}}^2 \quad (1.4)$$

Because

$$J = \Sigma_p \cdot E \quad ; \quad (1.5)$$

Σ_p is height integrated Pedersen conductivity and E is the electric field in this equation. Usually conductance which is the height integrated Pedersen conductivity over the most important height range is used instead of conductivity as expressed in formula (1.6).

$$\Sigma_p = \int_{90 \text{ km}}^{250 \text{ km}} \sigma_p(z) dz \quad (1.6)$$

Pedersen conductivity is found from the conductivity tensor which also includes Hall conductivity (σ_H) and parallel conductivity ($\sigma_{||}$). The expanded form is given as:

$$\sigma = \begin{pmatrix} \sigma_p & \sigma_H & 0 \\ -\sigma_H & \sigma_p & 0 \\ 0 & 0 & \sigma_{||} \end{pmatrix} \quad (1.7)$$

$$\sigma_p = \frac{eN_e}{B} \left(\frac{w_e v_{en}}{w_e^2 + v_{en}^2} + \frac{w_i v_{in}}{w_i^2 + v_{in}^2} \right) \quad (1.8)$$

As clearly seen from equation 1.8, σ_p is dependent on the collision frequency of ions (v_{in}), and electrons (v_{en}) as well as the electron density (N_e), magnetic field magnitude (B), electron and ion gyro-frequencies (w_i, w_e) (Schlegel, 2006).

For the calculation of Joule heating and auroral particle precipitation one of the most traditional methods is to use geomagnetic indices AU and AL and to calculate Joule heating with a function of the form

$$JH[GW] = aAE[nT] + b \quad (1.9)$$

a and b are constants which are chosen according to the number of stations included in deriving AE index. Ostgaard has given a table for a and b values that have been used to estimate JH in previous studies. According to the correlation constants given, it is seen that Ahn et al. have derived the most efficient regression function which was also used in this thesis study to estimate Joule heating using AE (2002). This can also be seen in Table 1.2.

Table 1.2: Hemispheric Joule Heating dependence on AE

	a [GW/ nT]	b [GW/ nT]	Number of Stations	HS.	Correlation Coefficient	Season
Ahn et al. (1983)	0.23	0	12	N	-	Spring
Ahn et al. (1983)	0.19	0	71	N	-	Spring
Baumjohann et al. (1984)	0.32	± 5	12	N	0.74	Spring
Baumjohann et al. (1984)	0.33	± 5	71	N	0.87	Spring
Ahn et al. (1989)	0.33	0	12	-	0.90	Summer
Cooper et al. (1995)	0.28	-20	AMIE	N	0.62	Fall
Lu et al. (1998)	0.20	43.4	68	S	0.76	Summer

The function Ahn et al (1983) has used was for a=0.33, and b=0.0 with a correlation coefficient of 0.90 with a number of 12 stations.

Tanskanen also used a geomagnetic index for the calculation of Joule Heating. However, the proxy she used was derived from Scandinavian sector magnetometer chain. She investigated 839 substorms in total and found out that JH corresponded to 30% of the solar wind energy input during the years 1997 and 1999. The coefficient she used was 3×10^8 , and instead of AE she used IL. The best correlation coefficient she found between epsilon and the joule heating values was 0.71 (2002).

Global Joule heating rate can also be estimated using global electric field maps from radar measurements and Pedersen conductivity maps driven from satellite measurements (Palmroth, 2003). As an example, Baker et al. conducted a study by using SuperDARN radar network data and TIMED Spacecraft Global Ultraviolet Imager data to estimate Joule heating. They have used Horizontal Wind Model for neutral wind contribution to Joule heating rates. As a result they have gained the spatial Joule heating rates, and stated that Joule heating is the dominant heat source for the sectors with weak auroral structures, but on the contrary strong electric fields (Baker et al., 2004). On the other hand, Palmroth (2005) expressed that averaged measurements like multiplying data sets lead to an overestimation in Joule heating rates, while Deng et. al. emphasized the underestimation of Joule heating in absence of small scale structures (2007).

2. MODELS

2.1 SWMF/BATSRUS

Space Weather Modelling Framework/ Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme was first developed by University of Michigan scientists. Model also takes into account the ionosphere-magnetosphere couplings and is based on an MHD code which can be run parallel. Its input consists of solar wind upstream values. The model by interpolation and analytical methods solve MHD equations and gives out the structure of the magnetosphere at the event time. Several modules starting from Solar Corona (SC), Inner Heliosphere (IH), Solar Energetic Particles (SP), Global Magnetosphere (GM), Inner Magnetosphere (IM), Radiation Belt (RB), Ionosphere Electrodynamics (IE), Upper Atmosphere (UA) are included.

Global magnetosphere and ionosphere electrodynamics modules are used to inspect magnetospheric configuration and to derive Joule Heating in this thesis. Global Magnetosphere module computes the magnetic field values and shocked solar wind values as well as the magnetotail flows and reconnection estimates. Ionosphere Electrodynamics takes the field aligned current values and using a statistical auroral conductance model which uses F10.7 flux calculates the ionospheric parameters like electric potential, Pedersen and Hall conductivities (Kuznetsova).

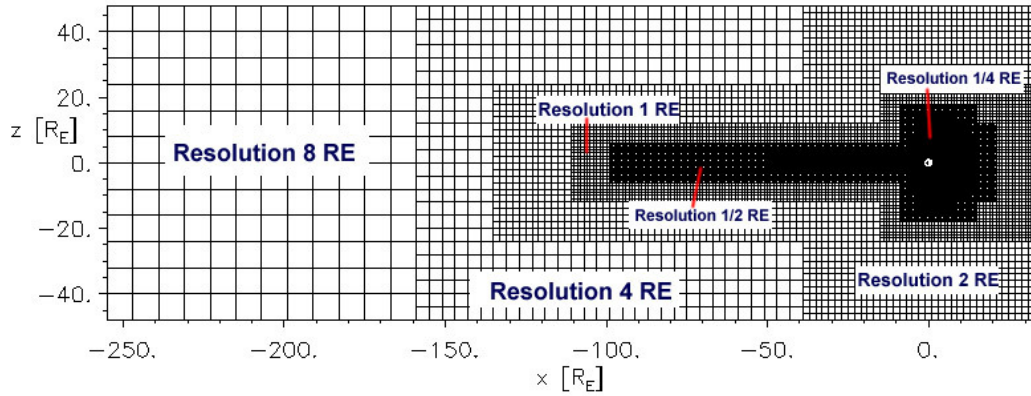


Figure 2.1: Grid structure of SWMF/BATSRUS

The model resolution grid can be selected. In Figure 2.1 , the grid structure is shown. Grid resolution is least in near Earth environment with $\frac{1}{4}$ Re, and most after 150 Re in magnetotail region with 8 Re.

2.2 Conductivity Models

For conductivity, there are three types of models. Generally they all include the statistical and empirical relationships. In this section three models used in this study will be presented.

2.2.1 Empirical-statistical models: Heppner-Maynard Model

Heppner Maynard model was written in 1987 by Heppner and Maynard as a FORTRAN code. The model includes the statistics coming from successful passes of DMSP satellite, and takes Kp index and IMF By, Bz pattern as input. It first generates the ionospheric potentials then using those values, electric fields are generated. This model also computes Joule heating intrinsically (Rich et al., 1989).

2.2.2 Standard Models: IRI-2007

IRI- International Reference Ionosphere model is updated occasionally. The data it uses comes from ionosonde, incoherent scatter radar, ISIS & Alouette topside sounders, satellite, rocket in situ measurements. It is an empirical standard model providing monthly averages of electron density, temperature, ion composition, ion temperatures from 50 km to 2000 km altitude (Bilitza et al., 2007).

2.2.3 Simulations: Semi-Empirical Auroral (BATSRUS):

Model uses solar EUV ionization empirical model that depends on solar 10.7 cm flux and the solar zenith angle, nightside background conductance, auroral oval conductance (empirical relationship between the field-aligned currents and local conductance derived using the AMIE technique), and constant polar cap conductance. It is included in SWMF/BATSRUS code.

3. DATA SOURCE

To investigate substorms and storms we have to use combined data sources. On the ground: magnetometers, radars, all-sky-cameras, and in magnetosphere near Earth orbiting satellites, solar wind monitoring satellites and satellites sent with scientific purposes to track the signatures. All of this data should be treated carefully to determine cause and affect relationships.

3.1 Satellites: THEMIS Mission

THEMIS spacecraft has been launched in February 2007 to study primarily the formation of substorms. Using five identically designed spacecraft and carrying the instruments which are built by the state of the art space technology, the main objectives of THEMIS spacecraft are to establish when and where the substorm in the magnetotail starts and identify the differences between the CD and NENL models and integrate the information into a global view of the substorm formation. The orbits of the five space probes rotate around the Earth to study also the different phenomena other than the substorms in the magnetospheric system as an auxiliary purpose. Figure 3.1 shows a sketch of the THEMIS spacecraft orbits in the tail (first panel from right) and on the dayside (second panel from left). While the THEMIS spacecraft have been placed in highly elliptical orbits, the five probes line up on the same plane at their apogees at every four days. This gives a very good opportunity to study the substorm phenomena in the tail (Angelopoulos, 2007).

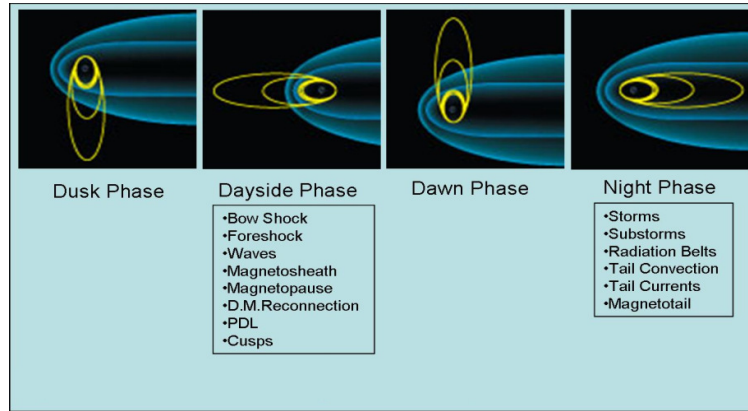


Figure 3.1: THEMIS mission (themis website)

3.2 SuperDARN

SuperDARN network is a group of coherent scatter radars. Each radar is directed to a portion of the high latitude ionosphere. The field of view of radars is such that the convection pattern due to ion motions can be inspected (Ruohoniemi et al. 1998). The locations of the radars can be seen in Figure 3.2. Coherent scatter radar technique measures the ion velocities provided the F region ion density irregularities in line of sight. Potential and electric field are found by spherical harmonic fitting techniques assuming that irregularities are parallel to magnetic field vector $\mathbf{B}$, and the ion motion is the drift motion $\mathbf{ExB}$ (Baker et al., 2004).

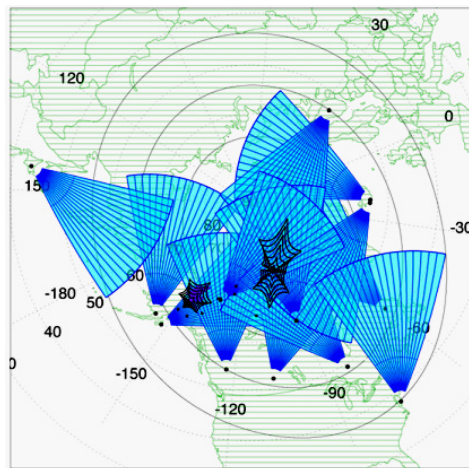


Figure 3.2: SuperDARN HF radar locations (Bristow, 2006)

Figure 3.2 shows the location and field of view of radars.

3.3 Ground Station Products and Indices Used

Proxies are used for calculating the disturbance time currents and changes in ionosphere like Joule heating and auroral particle precipitation estimations. They are mainly based on magnetometer measurements. Here, AE, Dst, and Kp indices will be introduced.

3.3.1 AE

AE is the abbreviation for auroral electrojet index. It is very much proven to be useful in Joule heating calculations. AE index is mainly calculated by AL and AU which show the changes in ionospheric conductance and electrical currents as they are calculated using the magnetic field disturbances at the auroral stations. Eastward and westward jet intensities are provided with the help of AU and AL, consequently giving the total horizontal flow as AE values. AU corresponds to the strength of eastward electrojet while AL corresponds to the strength of the westward electrojet. However, AE index may not be very accurate sometimes due to lower latitude auroras than the AE stations. In figure 3.2 You can see the AE stations located on northern hemisphere.

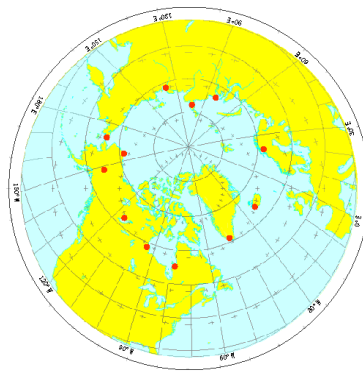


Figure 3.3: AE stations

3.3.2 Dst

Dst (disturbance storm time) index is derived using the horizontal component of magnetic field. The index is a combination of averaged magnetic field values of stations all over the world located at the equatorial latitudes. The signatures of a magnetic storm or substorm can be easily seen in the Dst variations.

Any negative value of Dst is a sign of the ring current injection, thus, a magnetic storm which only results from southward IMF (Baumjohann et al., 1996). This index is also described as the ring current index. The total energy in drifting particles which create storm time ring current is directly proportional to Dst and inversely proportional to Earth's magnetic field strength. When dynamic pressure enhances, Dst becomes more positive (Russell et al., 2000).

3.3.3 Kp

Kp index is the planetary range index (Balch). IMF magnitude and daily averages of solar wind velocity are correlated with this index (McPherron, 1991). By means of Kp, solar particle radiation's influence on geomagnetic disturbances is investigated. Data set consists of 3 hour values, and is the average of 13 subauroral stations measuring the two horizontal field components and calculating the K index. K variation is only seen when there is geomagnetic activity present (Balch).

3.3.4 Coordinate systems used

- i) Geocentric Solar Magnetospheric (GSM) – for data
 - a. X toward the Sun
 - b. Z in the plane determined by X and magnetic North Pole pointing toward the North Pole
 - c. Y in the magnetic equator perpendicular to Z.
- ii) Geocentric Solar Ecliptic (GSE) – for satellite locations
 - a. X toward the Sun
 - b. Z perpendicular to ecliptic plane
 - c. Y in the dipole equatorial plane perpendicular to X.

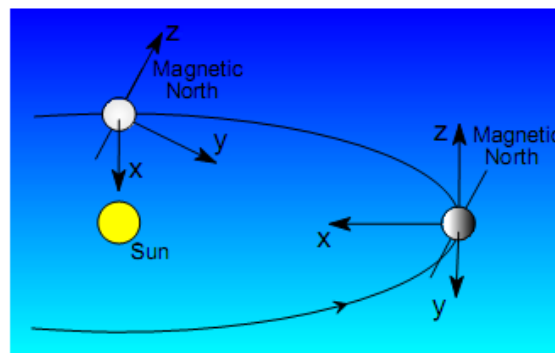


Figure 3.4: GSE coordinates

4. ANALYSIS, RESULTS, and DISCUSSION

4.1 Event Selection

To select the substorm events that we are going to present here, firstly, ground signatures were considered. Auroral activation was looked for as it is the most significant signature of a substorm. For this purpose, keograms were used to see if there are any auroral brightenings at high latitudes in northern hemisphere. A keogram shows the movements of auroral forms which correspond to different phases of substorms phases and is generated using all sky camera images at consequent times.

Figure 4.1 represents the keograms of McGrath (67°N), Gakona (62.4°N) and White Horse (61°N) stations. THEMIS ASI stations have time resolution less than 10 seconds and spatial resolution about 1° (Team, 2007). In keograms, especially in GAKO and WHIT the intensifications are seen after 12 UT pointing out a substorm in the magnetosphere.

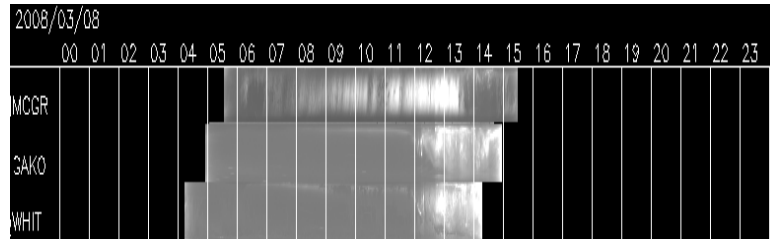


Figure 4.1: Keograms of McGrath (MCGR-USA), Gakona (GAKO-USA), White Horse (WHIT-Canada) from THEMIS All Sky Imaging Array (ASI)

Figure 4.2 shows the keogram of Sodankylä in Finland on March 8, 2008 when it was in night sector. This image is generated by taking vertical slices in 20 sec periods. According to this keogram, the activation first started at higher latitudes at 17:30 UT, and then expanded more equatorward with the brightening of the auroral arc around 18 UT in Finland sector. The substorm ended at around 19:30 UT with a poleward retreat and decrease in the luminosity of aurorae. Three intensifications can be seen from the keogram image during this time interval.

To conclude, two substorms were observed in March 8, 2008. The first substorm signatures were observed in Canadian sector night while the second substorm signatures were apparent in European sector night.

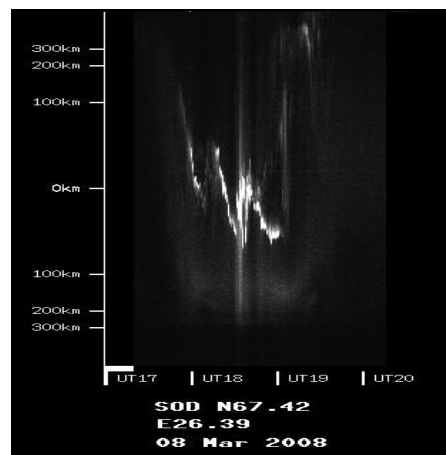


Figure 4.2: Keogram of Sodankylä

4.2 Ground and Ionospheric Signatures

The signatures of substorms can also be seen in ground magnetometers. In Figure 4.3 geomagnetic field data from four stations of IMAGE magnetometer chain were plotted. The stations selected were KEV (Kevo: 69.76°N, 27.01°E), TRO (Tromsø: 69.66°N, 18.94°E), LYC (Lycksele: 64.61°N, 18.75°E) and RVK (Rørvik: 64.94°N, 10.98°E). The length of the lines on the left of the plots signify 500 nT change where X is the northward, Y is the eastward, Z is the vertical (positive downward) component. It is seen that the largest change of the geomagnetic field was in the X component, and it was larger during the first substorm. The onset of the first substorm from magnetometer data is seen to occur at 12:10 UT due to the sudden decrease in X component, with first intensification at 13:00, and last intensification

at 14:25 UT. Following the last intensification the situation recovers to background values until the second substorm with an onset at 17:10 UT starts. Substorm onsets are marked with red dashed lines, while the intensifications in the expansion phase are marked with blue dashed lines in the plot. During the second substorm, KEV and TRO measured negative deviations while LYC and RVK which are in lower latitudes measured positive deviations. This suggests a vortex formation in between 64.5-69.5°N latitudes as a negative deviation of X component means a westward electrojet and a positive deviation of X component indicates eastward electrojet.

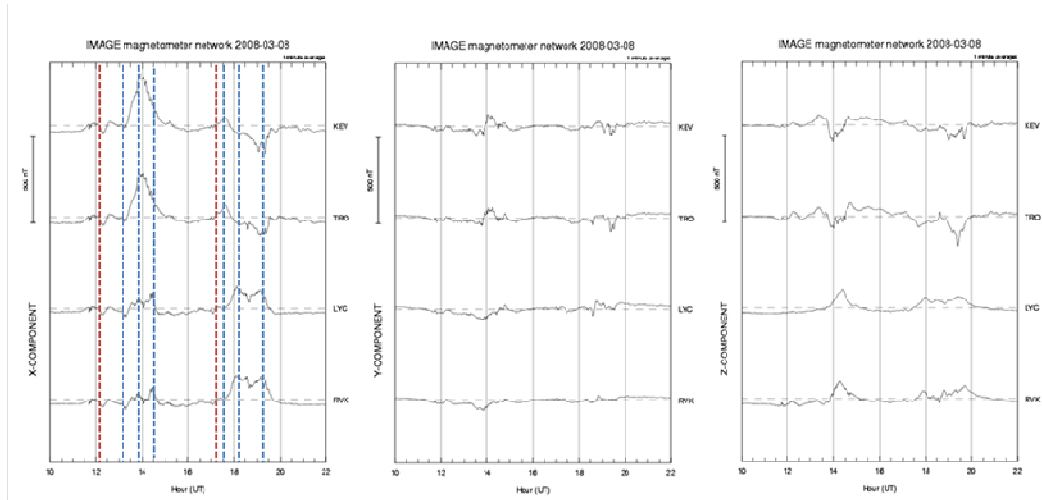


Figure 4.3: IMAGE magnetometer records for March 8, 2008

The resulting changes in auroral electrojet indices in March 8, 2008 can be seen in Figure 4.4. The data were taken from World Data Center, Kyoto. In the figure, S, represents the start of the substorm, G, growth phase, E, expansion phase, R, recovery phase, and O the expansion onsets. Several intensifications in westward electrojet were observed during the first substorm expansion phase, which lasted from 12:10 UT to 14:10 UT, indicating an enhanced period of electrical conductance in the ionosphere. AL values (red line) reached up to 800 nT. On the other hand, the second substorm observed on the same day had smaller values around 500 nT. The expansion phase of the second substorm started around 17:10 and ended at 18:45 UT. After 18:45 the recovery phase of the second substorm started so that the ionospheric conductance turned back to its normal values. Both of the substorms were moderate substorms with AE indices less than 1000 nT.

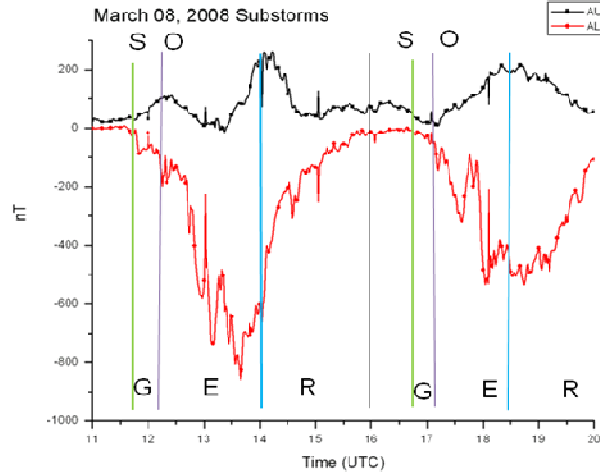


Figure 4.4: AE index for March 8, 2008

Figure 4.5 shows the equivalent currents corresponding to March 8, 2008 substorm. The equivalent currents were calculated using the open-access tool from Finnish Meteorological Institute web page with 60 sec. resolution. The calculation interval was from 11:00 UT to 22:00 UT with baseline (undisturbed period) at 04:00 UT and 05:00 UT in March 8, 2008 close to the event from IMAGE magnetometer chain data.

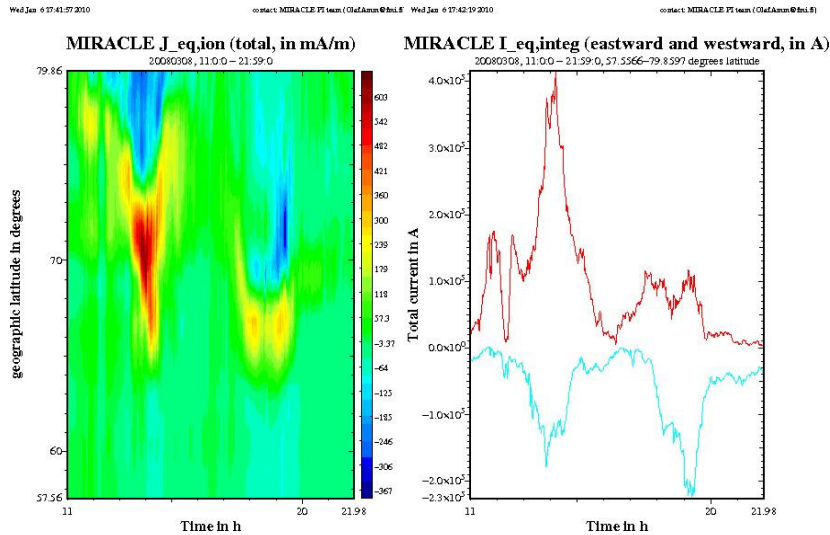


Figure 4.5: Calculated equivalent ionospheric currents

For the calculation, it is assumed that currents only vary in north-south direction and don't change in east-west direction (Amm, 2004).

On the left, the current distribution in north-south direction was plotted in mA/m units with colored areas where red (positive values) denotes eastward flowing currents, while blue (negative values) denotes westward flowing currents. There are two intensification periods for both eastward and westward electrojets which coincide with the substorm intervals we study here. The expected configuration of eastward and westward electrojets in the ground magnetograms is also evident in Figure 4.5 for the second substorm around 68°N latitudes.

On the right panel in Figure 4.5, total integrated equivalent currents are given in units of Ampere. In the figure, we see that the eastward electrojet is stronger during the first substorm with a maximum of about $4 \cdot 10^5$ A, whereas it is the westward electrojet which is seen to be stronger during the second substorm with a maximum of about $2.3 \cdot 10^5$ A.

Dst index, determined based on the ground magnetic field measurements, was used to decide whether the observed substorms were isolated or storm-time substorms. Here we adapted the value given by Tanskanen, -40 nT, which corresponds to the upper limit of Dst to assume the events as isolated substorms.

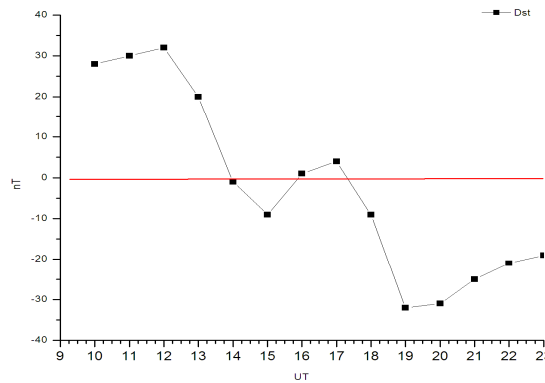


Figure 4.6: Dst index on March 8, 2008

In Figure 4.6, it is clear that Dst did not reach greater values than -35 nT, being within the limits of isolated substorm definitions. Therefore, our substorms are isolated substorms.

4.3 Solar Wind Conditions

To see the cause of substorms observed on the ground and ionospheric level, solar wind parameters were examined. First, a broader time interval was selected to detect any large disturbances coming from the Sun like CMEs. Starting from March 7 till March 10, concurrent upstream solar wind parameters such as the interplanetary total magnetic field, IMF B_z component, velocity, density, dynamic pressure and temperature taken from upstream WIND spacecraft, which was located at $\sim 198.6 R_E$, were presented in Figure 4.7.

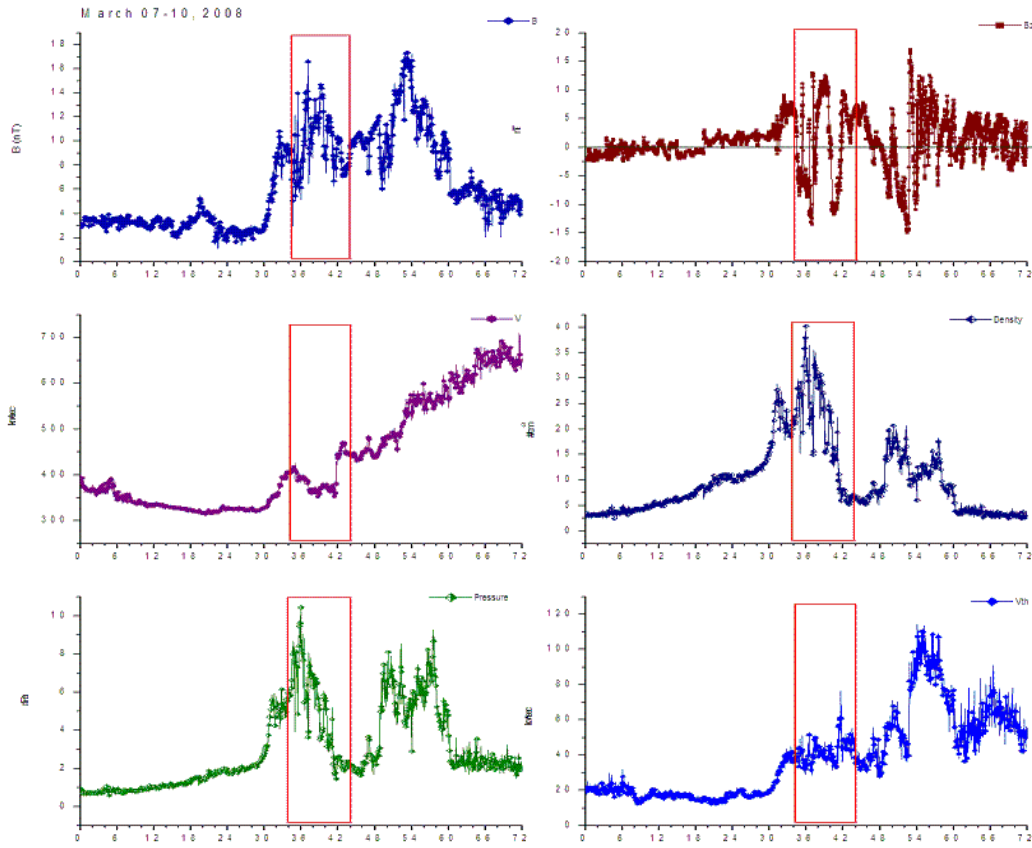


Figure 4.7: Solar wind parameters corresponding to March 8, 2008 substorm. Time axis runs from the start of March 7 to the end of March 10 2008.

In Figure 4.7, the red boxes show the time interval corresponding to the geomagnetic disturbances on Earth. Presence of a CME can easily be noticed in the high density and high velocity panels resulting in stronger pressure which compresses the magnetosphere on the dayside. In Figure 4.7, density and velocity values reach up to 40 particles/cm³ and 450 km/sec respectively at the beginning of the CME event.

Specifically looking at the time interval we are interested in, it can be seen that solar wind upstream velocity values were about 384 km/sec for the first substorm and 423 km/sec for the second substorm on the average. The upstream data were shifted in time by the equation given in Eq. (4.1) to account for the solar wind convection time from the Wind spacecraft to the dayside magnetopause. , distance of bow shock from magnetopause, Alfvenic interaction (2 min.) and position of the WIND spacecraft as well as the velocity of the solar wind as given from Zhang et al (2005).

$$t_{prop} = \frac{X_{wind} - X_{mp}}{V_{sw}} + t_{Alfven} + \frac{D_{bs}}{V_{sw}} \quad (4.1)$$

where

$$X_{mp} = \sqrt[6]{\frac{M^2}{\mu_{oc} n m V_{sw}^2 \cos^2 \theta}} \quad \text{and} \quad (4.2)$$

$$D_{bs} = X_{mp} \left[1.1 \left(\frac{\gamma - 1}{\gamma + 1} \right) \right]$$

$$\gamma = \frac{5}{3} \quad (4.3)$$

In the equations, M is the magnetic moment of the Earth, μ is the magnetic permeability, n is the number density, m is the proton mass, V_{sw} is the upstream solar wind velocity, X_{mp} is the magnetopause distance, D_{bs} is the bow shock distance from the magnetopause.

Table 4.1: Solar wind data for Time Shift

V_{sw} (km/sec)	X_{mp} (Re)	D_{bs} (Re)	t_{shift} (hours)
384,0081	6,977122	1,904282	0,92578
423,1752	8,252883	2,252479	0,84057

Figure 4.8 gives IMF B_z , P_{dyn} , magnetopause distance at the subsolar point, number density and velocity respectively from top to bottom for two of our substorm events.

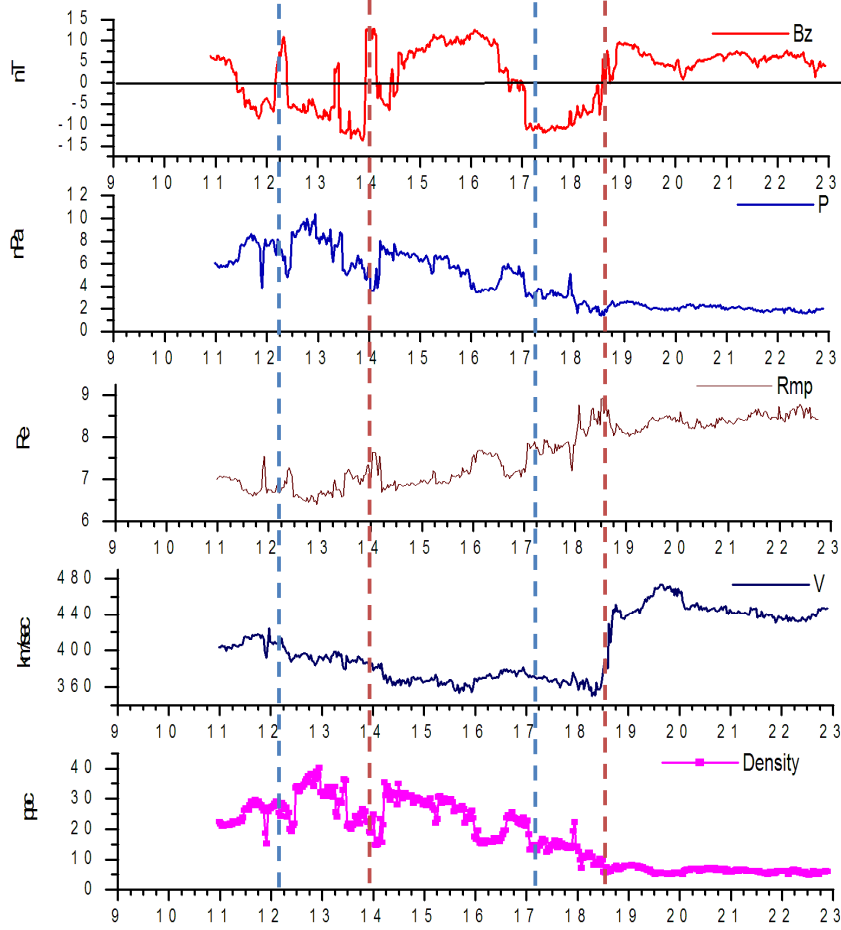


Figure 4.8: Expanded time interval of upstream solar wind parameters for the substorms of March 8, 2008

The onsets of the substorms are marked with blue lines and end of expansion phase (beginning of the recovery phase) with red dashed lines in Figure 4.8. IMF B_z values drop to -15 nT and negative IMF B_z lasted more than one hour for both substorms. The average density of the upstream solar wind is about 3 to 6 ppc before our substorm events, but in March 8, 2008 density values up to 40 ppc were observed and the mean stayed around 30 ppc during the first substorm. The average particle number density during the second substorm dropped to 15 ppc. Magnetopause distance responds to the changes in the upstream solar wind density and velocity as given in Eq. 4.1.

In this case, it is mostly the density variations that control the magnetopause motion. Simple calculations at the subsolar point show that the magnetopause during the expansion phase of the first substorm was pushed towards the Earth by about 3.5 Re from its nominal position of 10 Re. Owing to the increase in density and dynamic pressure, it is seen to be about 6.5 Re in Figure 4.8.

4.4 The Magnetosphere

In this section magnetospheric structure and configuration during the time when we see the most intense electrojets (AE index) corresponding to the expansion phase of both substorms will be inspected. For the first substorm it was 13:30 and for the second substorm it was 18:00 which can be seen in Figure 4.4 in previous section. We demonstrate this by looking at the global MHD simulation results corresponding to our substorm events as presented below.

BATSRUS MHD model was run for nine hours starting from March 8, 2008 10:00 UT, and ending at March 8, 2008 22:00 UT. Upstream solar wind parameters from Wind spacecraft presented in Figure 4.8 were given as the input. The values were propagated to 33 Re which is the boundary condition on the dayside magnetosphere for the model. Inflow boundary conditions were set as time-dependent, and model was also run with the Rice Convection Model with a grid resolution of 755.136 cells. Dipole tilt in X-Z plane was set to -7.4 degrees and dipole tilt in Y-Z Plane was set to 12.2 degrees for March 8, 2008 at the beginning of the run, and those were updated with real time within the model. The output values were requested in GSM coordinates with 300 seconds resolution.

The magnetosphere at 13:30 UT and 18:00 UT are shown in Figure 4.9a and b. In panel a vectors represent IMF Bz while the lines are the magnetic field lines. Velocity values are represented with color regions. The cut plane was chosen at $y=0$ and IMF Bz was southward at the simulation time. Blue regions refer to negative velocity values which mean tailward velocities whereas red regions refer to positive values of velocity which mean flow towards Earth. The snapshot of the region between 30 Re and -60 Re at 13:30 UT was given. The model shows the reconnection region at about $x=-11.7$ Re as there are flows spreading out in both directions: earthward and tailward. The closed field lines beyond 15 Re are the

signature of a plasmoid travelling tailwards. Dayside reconnection is also apparent in the plot from the streamlines moving tailwards from dayside. The small insert on the right of the panel a gives the expanded region of the tail reconnection site. Tail reconnection site is distinctly visible in XZ and YZ planes (X: -15 Re to 10 Re, Y: -2.5 Re to 2.5 Re, Z: -5 Re to 5 Re). Red lines represent magnetic field lines, while colored areas and vectors represent the number density of particles and the velocity respectively. While earthward of $x = -11.7$ Re, the velocity vectors point towards Earth, they point toward tail tailward of $x = -11.7$ Re. Also in panel b the colored regions show the number density of particles, streamlines magnetic field lines, and vectors, velocity of the flow at time, 18:00 UT. The region shown is from 15 Re to -35 Re. Red color illustrates the most populated regions. Magnetosheath can be identified on the dayside with its bright red color. Reconnection site is seen to occur at 8.5 Re which suggests a Near Earth Reconnection site. The entry of solar wind particles from dayside can also be seen in the green region extending into the polar cusp regions.

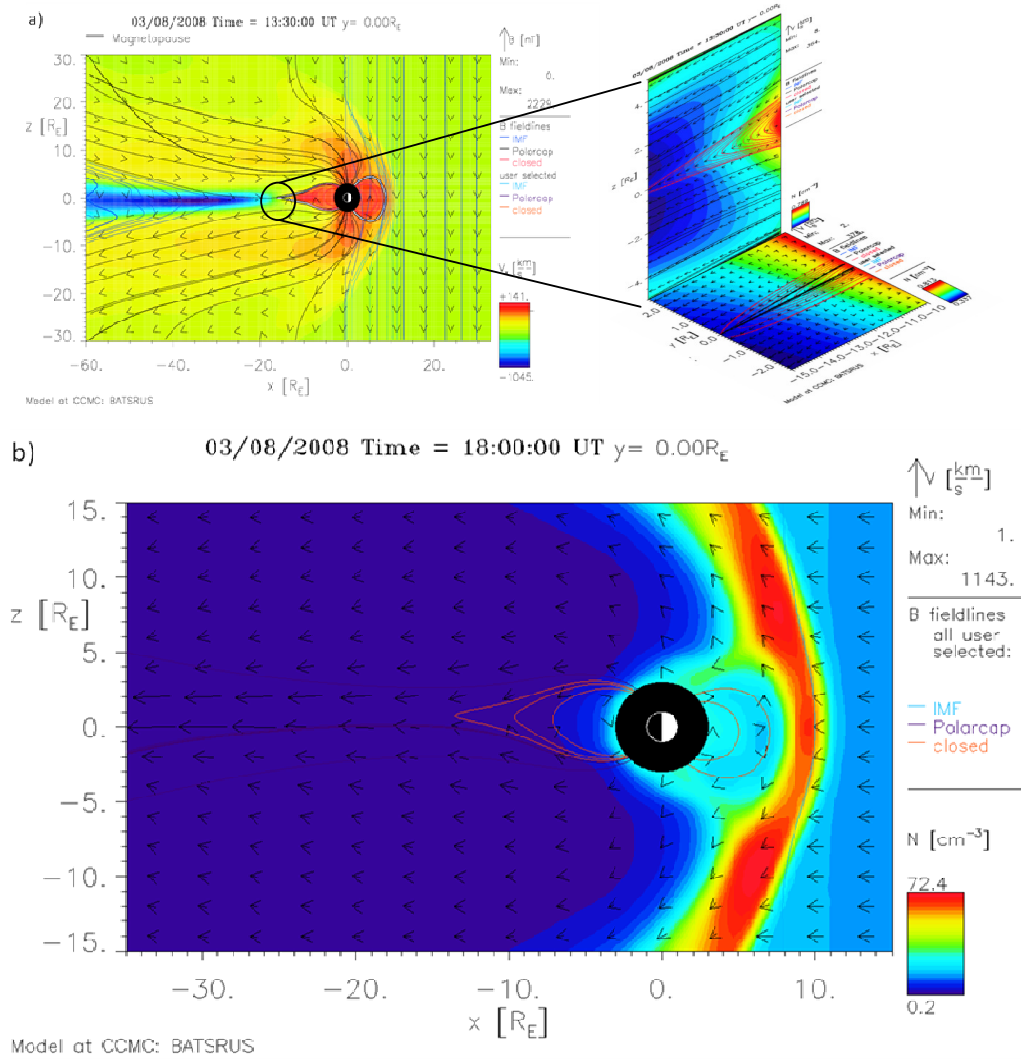


Figure 4.9: Magnetosphere at a) 13:30 b) 18:00

4.5 Magnetotail Flows

Magnetotail flows are studied in this section. Both BATSRUS MHD model and spacecraft measurements are used. Below spacecraft positions in the magnetotail are listed in Table 4.2.

Table 4.2: THEMIS Spacecraft Positions

Time	Sat.	GSE (Re)			Spacecraft Region
		X	Y	Z	
2008 68 13:30	ThA	-8.40	4.16	-3.16	Plasma Sheet
2008 68 13:30	ThB	-25.42	11.79	-6.57	Tail Lobe
2008 68 13:31	ThC	-14.93	10.37	-5.81	Plasma Sheet
2008 68 13:30	ThD	-7.50	-1.38	-0.78	N Magnetosphere
2008 68 13:30	ThE	-9.11	-0.35	-1.51	Plasma Sheet
2008 68 18:00	ThA	-8.52	0.93	-2.27	Plasma Sheet
2008 68 18:00	ThB	-24.29	10.22	-5.75	Plasma Sheet
2008 68 18:00	ThC	-16.23	9.39	-5.62	Plasma Sheet
2008 68 18:00	ThD	1.08	2.13	-0.57	D Plasmasphere
2008 68 18:00	ThE	-1.81	-2.45	0.52	N Plasmasphere

Spacecraft positions were taken from NASA Satellite Situation Center web site in Geocentric Solar Ecliptic coordinates, along with the probable spacecraft regions. D means dayside while N means nightside in the table. ThA , ThC, and ThE spacecraft were in the plasma sheet while ThD was passing through nightside magnetosphere and ThB was close to the tail lobe.

Most of the plasma in magnetotail is found in the region called plasma sheet. Plasma sheet is about 10 R_E thick in central tail plane. The importance of this region comes from the transport of plasma earthwards and tailwards. High latitude auroral ionosphere is also in extent of the plasma sheet (Baumjohann et al., 1996). Additionally it is known that background flow values are generally on the order of 50 km/sec within the plasma sheet inferred from the early statistical studies (Huang et al., 1986). High speed flows were also observed in the plasma sheet during both quiet and disturbed geomagnetic conditions. These high speed flows are usually 10 minute duration events having bursty nature (Angelopoulos et al., 1992). Baumjohann et al. investigated flows according to the regions of plasma sheet with a data set containing: 1250 inner central plasma sheet, 1100 outer central plasma sheet and 2950 plasma sheet boundary layer events (1990). Their criterion was 400 km/sec for bursty flows which also created earthward convection enhancements. However they noted that choosing 300 km/sec or 500 km/sec wouldn't change the statistical properties of the flow distribution. The faster was the flow, the shorter was the peak duration in these studies. Fairfield et al. presented a study relating magnetotail flows to auroral kilometric radiation intensifications, auroral brightenings, geosynchronous particle injections and magnetic activity (1999). AKR intensifications were seen within a minute of the flow bursts, and electric fields causing the acceleration also led to particle injections at geosynchronous distances according to their findings. Sergeev also stated that BBFs have auroral footprints attributable to the associated plasma precipitation and electric currents created in the ionosphere (2004). Recently Ohtani et al. carried out an investigation about the role of flows in flux transport in magnetotail using Geotail measurements (2009). They found out that local magnetic field became more dipolar with fast tailward flows and tailward flows are due to electric drift. They also added that earthward flows were observed prior to the tailward flows. Johansson et al. summarized the characteristics of BBFs as the following: 10 min. flow enhancements and 1 min flow peaks with decreased density, increased B and decreased plasma beta in the plasma sheet environment (2009).

Figure 4.10a and Figure 4.10b show the magnetic field configurations and spacecraft locations for 13:30 and 18:00 (at the maximum AE times). The magnetic field configuration was generated by BATSRUS MHD model. Satellites passing through the plasmasphere were not plotted as the data in plasmasphere was not used during this study.

Satellites were denoted by colored stars: ThA, blue, ThB, wine, ThC, green, ThD, purple, ThE, red. ThC and ThB were in the region of open field lines which have footprints in the polar cap region while ThA, ThD, ThE were on closed field lines for both substorms, and ThD on more dipolar field lines during the first substorm. In Figure 4.10 we have already seen that about 11.7 Re there was the magnetic reconnection taking place for the times chosen.

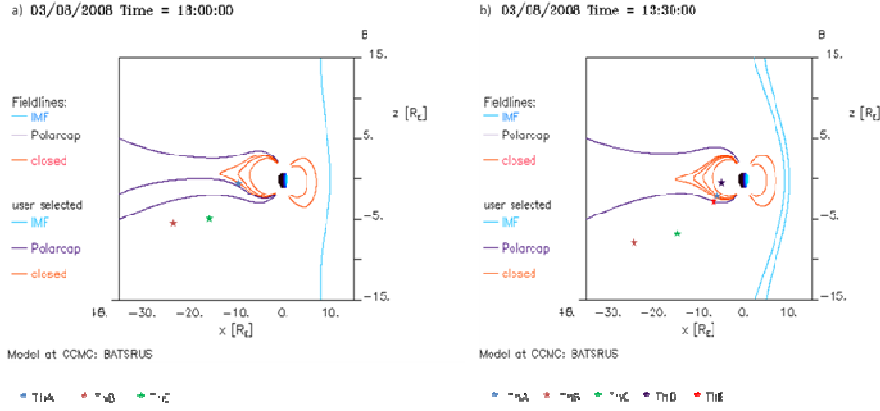


Figure 4.10: Magnetic field lines and satellite locations at a) 18:00 b) 13:30

AE, dynamic pressure of the solar wind and IMF Bz are shown in Figure 4.11 for the first substorm. Magnetotail flows under these conditions will be given in the following plots in which the data were taken from the THEMIS spacecraft. Start of the substorm was indicated with red lines, expansion phase with green lines and end of expansion and start of the recovery with magenta lines in all plots. The magnetic field data from THEMIS spacecraft are shown in red and blue, denoting z and x components, respectively. IMF Bz was mostly negative (southward) and average dynamic pressure was 7 nPa during the expansion phase. AE values reached to 1000 nT maximum during this time indicating a strong substorm.

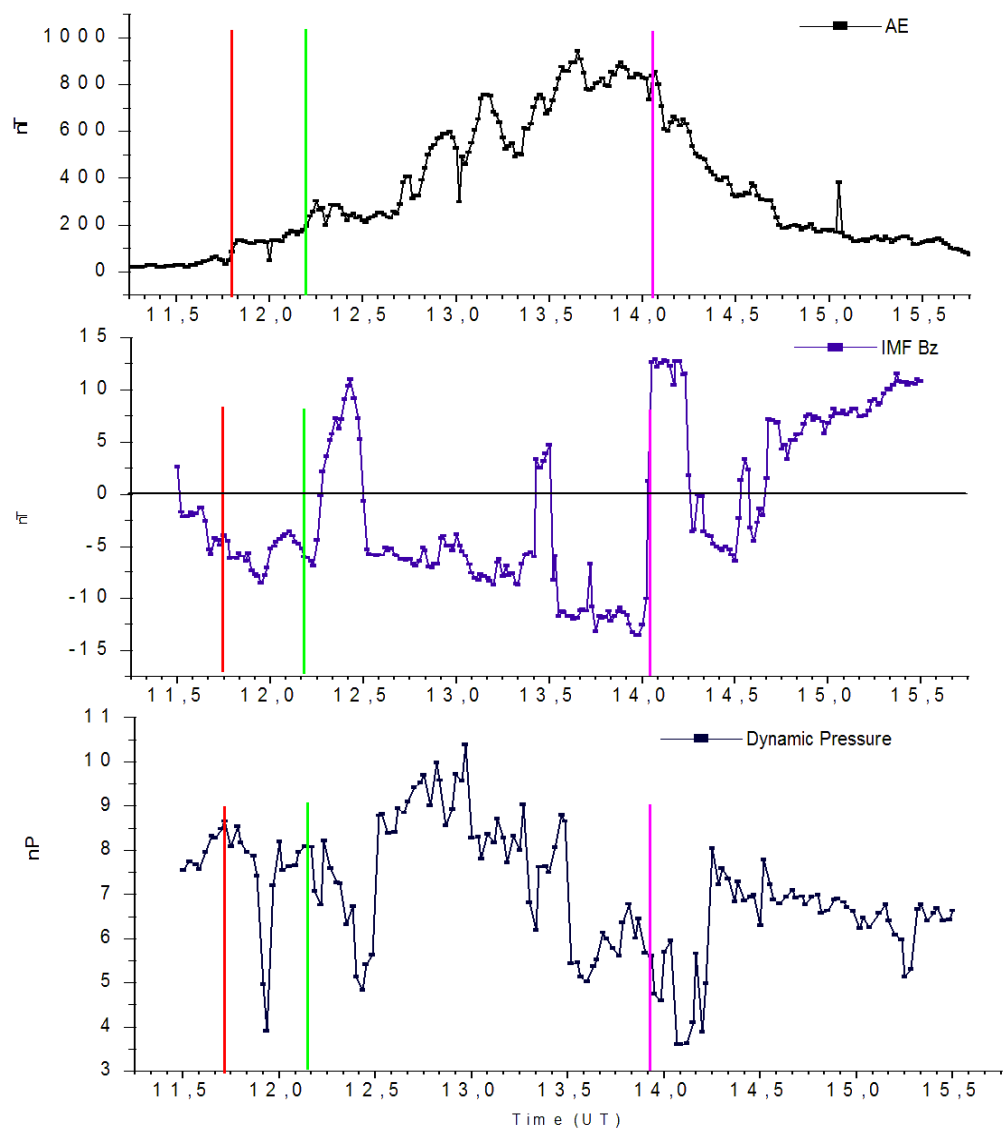


Figure 4.11: AE, IMF Bz, and Pdyn for the 1st substorm of March 8, 2008

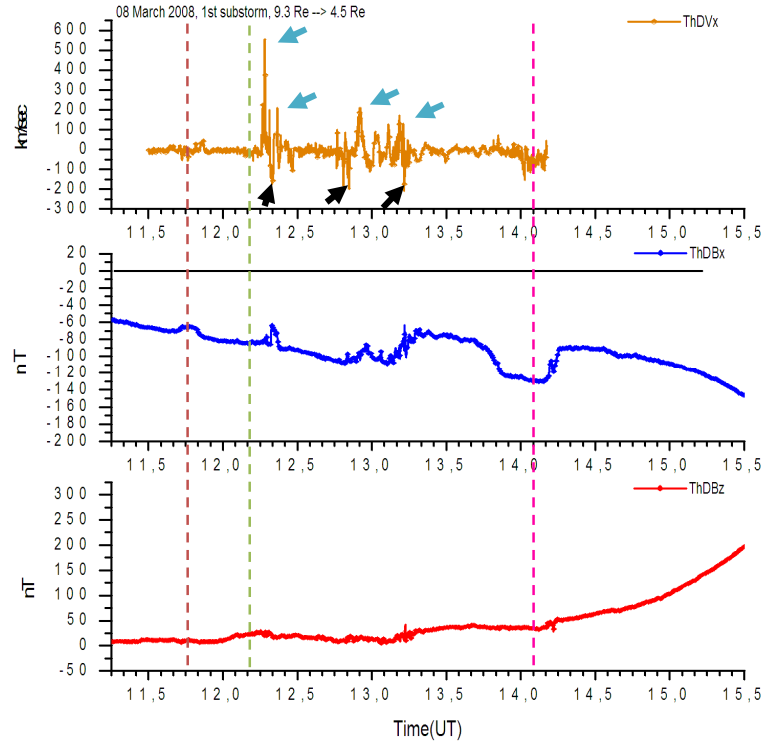


Figure 4.12: ThD measurements in magnetotail for the 1st substorm

The x and z components of the magnetic field along with x component of the velocity observed by ThD are shown in Figure 4.12. ThD was traveling from 9.3 Re to 4.5 Re during the first substorm, hence as a result, it observed stronger magnetic field components as it approached nearer to Earth. However, at distances of 8.5 Re it observed an earthward flow enhancement which indicates the characteristics of BBF both in temporal and spatial scale at ~12:13 UT during the expansion phase. Earthward flows are shown with blue arrows while tailward flows are shown with black arrows in the plots. The flow enhancements lasted about 10 minutes with a peak value of 600 km/sec accompanied by a tailward bursty flow afterwards, which matched with the findings of Ohtani et al. (2009). There were also several tailward flows on the order of 200 km/sec, and earthward flows with smaller magnitudes than BBFs also on the order of 200 km/sec observed during expansion phase. Tail Bz had a slight increase during the earthward flow, and tail Bx had an abrupt decrease which is also the evidence for the local dipolarization.

If considered together with Fig. 4.11 it can also be seen that IMF Bz was positive (in northward direction) during the BBFs, and lessen in southward direction in all cases of earthward flows, and was southward during tailward flows.

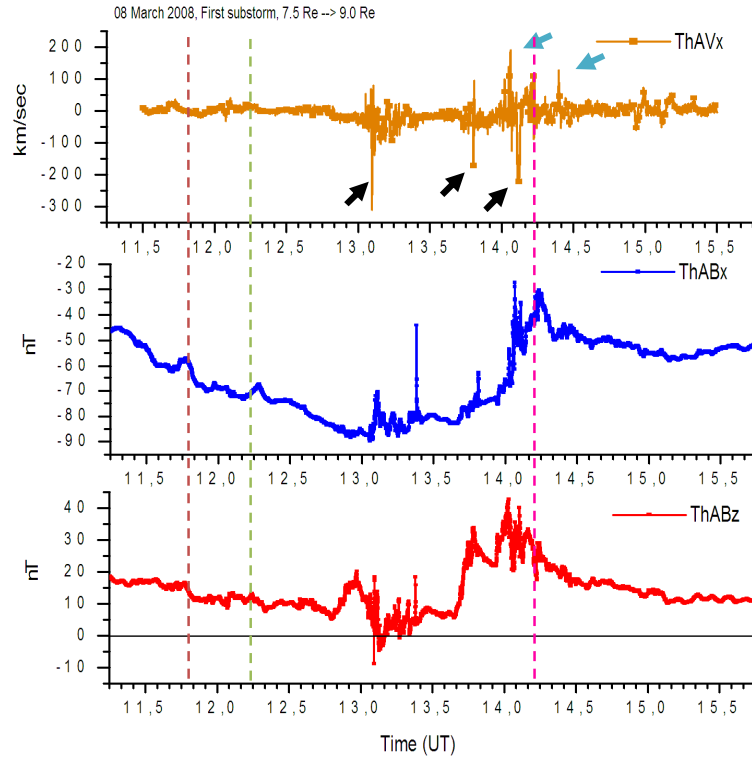


Figure 4.13: ThA measurements in magnetotail for the first substorm

ThA was the second nearest spacecraft to Earth traveled from 7.5 Re to 9.0 Re. It observed several flow enhancements, mostly in tailward direction ranging from 300 km/sec to 200 km/sec. It also saw some earthward flow enhancements but they didn't fit the criterion of 400 km/sec that Angelopoulos et al. (1992) defined. All flows both earthward and tailward coincided with decreasing magnitude of Bx component and increasing magnitude of Bz component presenting dipolarization in the magnetic field. Also examining Figure 4.11 and IMF Bz variations in Figures 4.12 and 4.13 concludes that the earthward flows were observed when IMF Bz was positive and tailward flows under southward IMF Bz directions. These enhanced flow periods were detected during the expansion phase of the substorms.

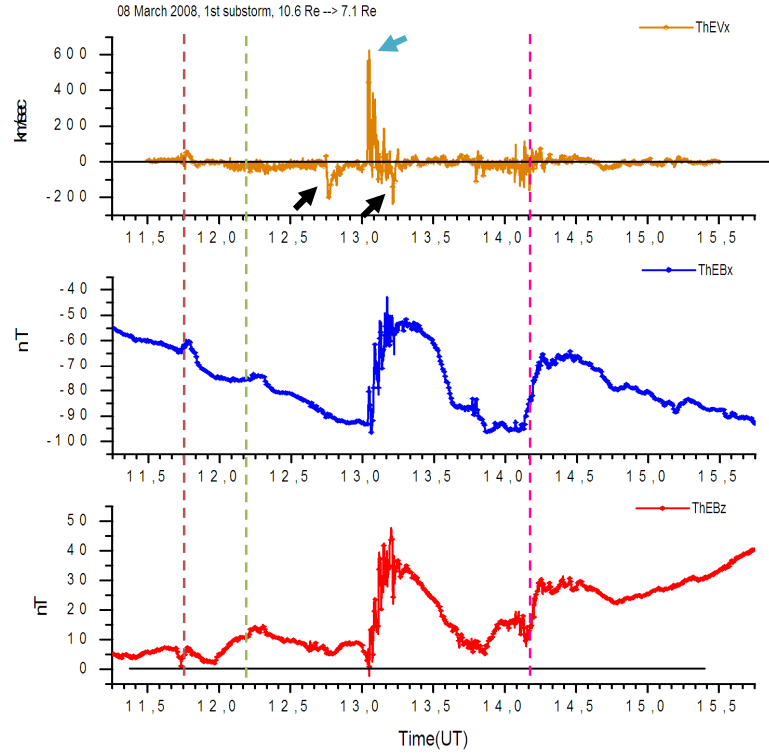


Figure 4.14: ThE measurements in magnetotail for the 1st substorm

ThE has moved from 10.6 Re to 7.1 Re when it observed a BBF at 13:00 UT. The peak of the BBF was 600 km/sec and nearly lasted more than a minute reaching up to values higher than 400 km/sec. Just before the flow signature, the Bx component becomes stronger, and Bz decreases to smaller values nearly to zero indicating that the tail field is stretching. Moreover, clear dipolarization was observed during the event time. In addition, IMF Bz becomes southward and decreased by about 2.5 nT in its strength. Tailward flows correspond to the intervals of strong southward IMF Bz conditions on the order of 10 nT.

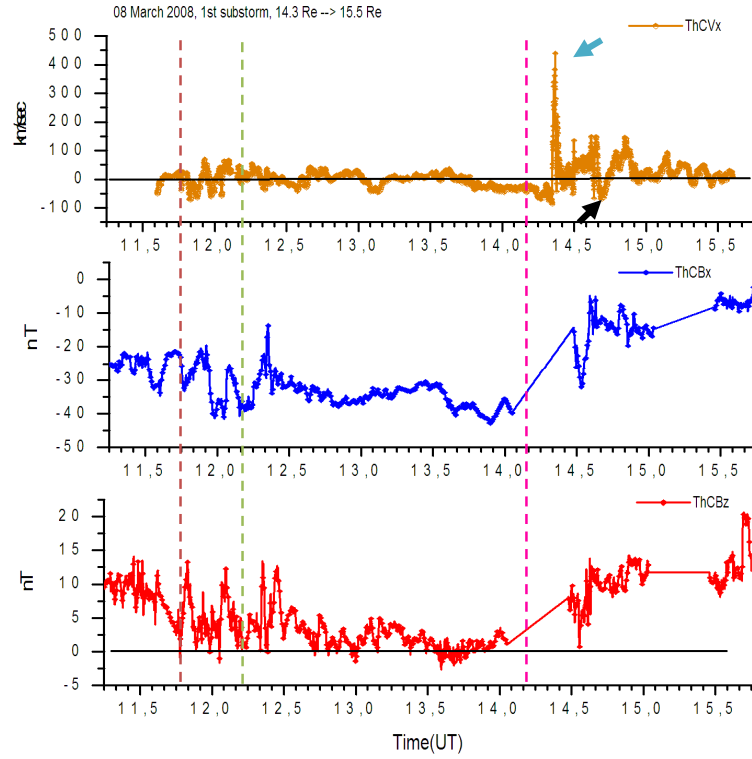


Figure 4.15: ThC measurements in magnetotail for the 1st substorm

ThC was further down in the tail around 15 Re on average. On the contrary to other spacecraft observations ThC observed BBFs and fast flows during the recovery phase as seen in Figure 4.15. There were some periods of absent magnetic field data, but the tendency is clear. The BBF that ThC observed had a maximum of ~450 km/sec and it occurred corresponding to the southward IMF Bz conditions, and the strongest tailward flow were measured to be about 100 km/sec.

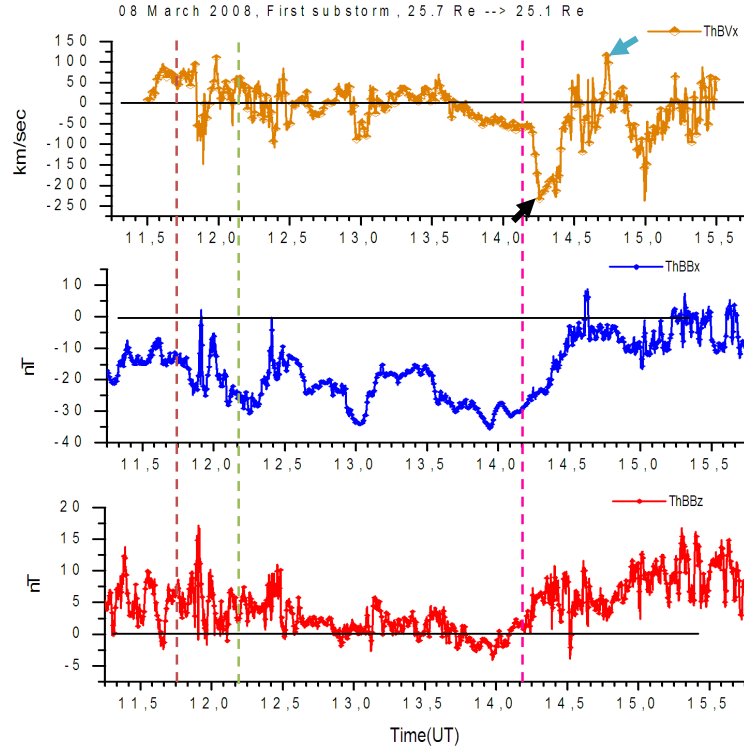


Figure 4.16: ThB measurements in magnetotail for the 1st substorm

ThB is the most tailward spacecraft in THEMIS constellation. It was in $x=-25$ Re distance to Earth during both substorm events. It didn't observe any significant earthward flows, but observed tailward flows of about 200 km/sec for about 15 minute duration. Right after this observation, was a period of earthward flow, just before another tailward flow enhancement. Bx was close to zero values, and Bz had recovered from zero values to 15 nT during the events. Examining solar wind conditions in Figure 4.11, we can see that those periods coincide with northward IMF Bz values.

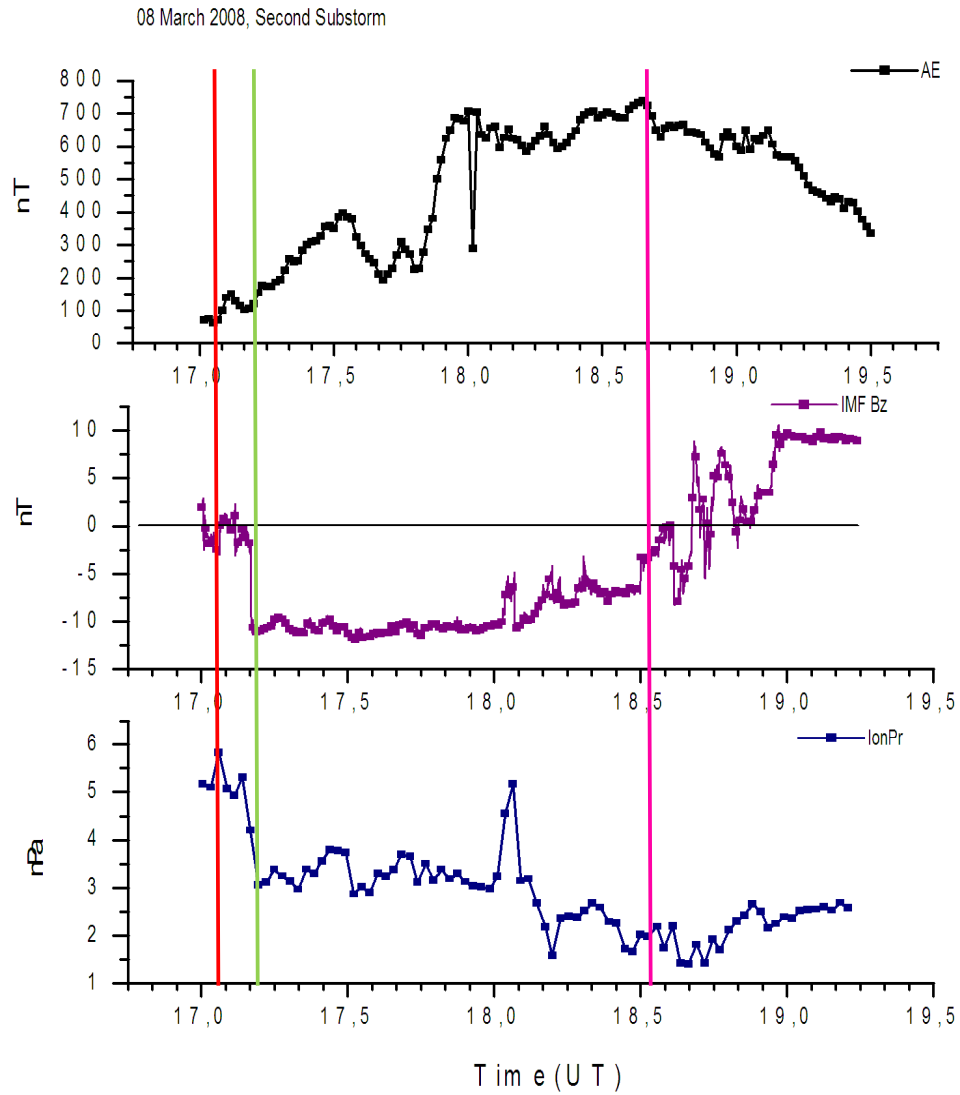


Figure 4.17: AE, IMF Bz and Pdyn for the second substorm of March 8, 2008

In Figure 4.17, AE, IMF Bz and Pdyn time series are presented for the second substorm. IMF Bz was southward throughout the expansion phase and turned northward, thus giving rise to the start of the recovery phase of the second substorm. Dynamic pressure changed from 2.5 nPa to 5.5 nPa around 18:00 UT. Later it decreased again. Magnetotail flows for the second substorm are shown in the following figures which are given in the same format of the first substorm.

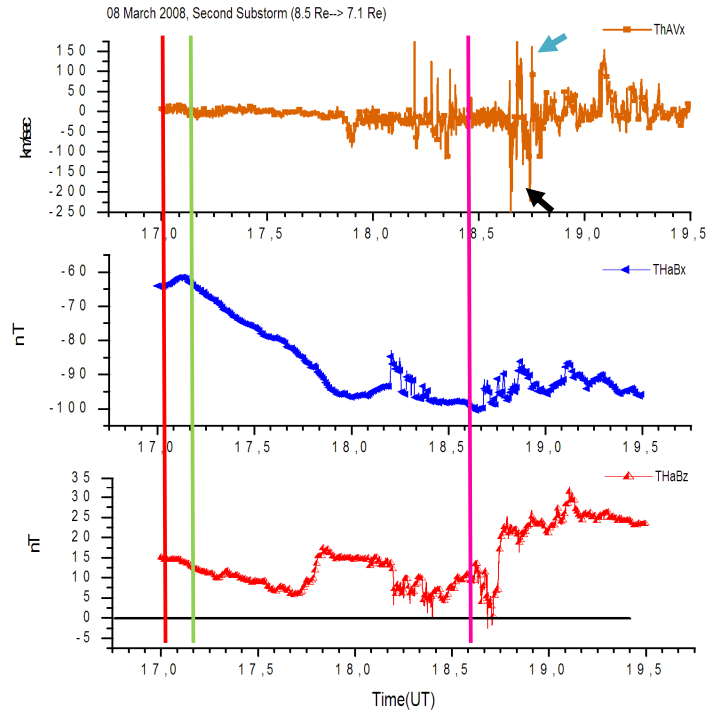


Figure 4.18: ThA measurements in the tail for the second substorm

Figure 4.18 shows the second substorm conditions observed by ThA which was travelling from 8.5 Re to 7.1 Re. There were several flow peaks, but none of them were sufficient to be defined as BBFs. Faster flows in tail were observed especially in recovery phase and all were associated with the dipolarization signatures of the field. Additionally, Figure 4.16 indicates that the earthward flows correspond to northward or less strong southward, IMF Bz times.

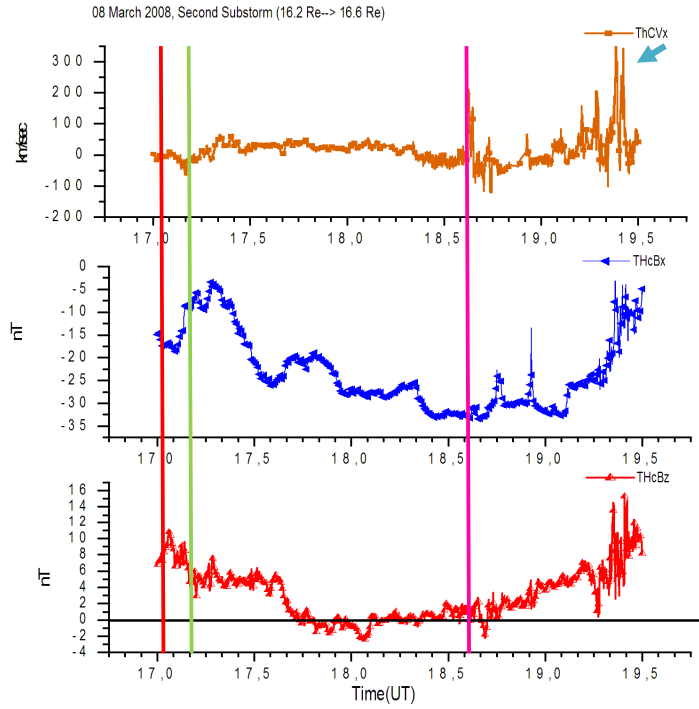


Figure 4.19: ThC measurements in the tail for the 2nd substorm

ThC also observed faster flows during recovery for this substorm as seen in Figure 4.19 when IMF Bz was northward throughout the event interval. ThC was located $x = \sim -16$ Re. In expansion phase the tail became more stretched since Bz values were close to zero and Bx values were high, but this situation changes with time, and the satellite moves toward more dipolar field regions. Bx gradually decreases to zero and Bz is about 16 nT.

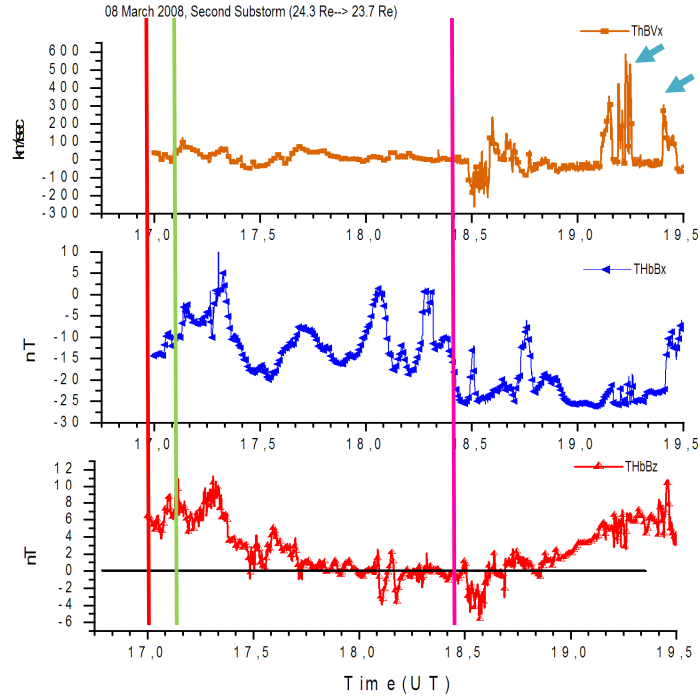


Figure 4.20: ThB measurements in the tail for the 2nd substorm

ThB was at the farthest point in the magnetosphere during the second substorm as well. It observed a clear BBF in the recovery phase lasting about 15 minute starting at 19:05 UT. This flow was not followed by any tailward flow, but rather with a second interval of high speed earthward flow burst. Flow speed stayed at about 520 km/sec for nearly 5 minutes. At the same time, Bz became increasing while Bx became smaller: a clear signature of dipolarization. IMF Bz was northward through out the interval and no significant dynamic pressure changes were observed.

4.6 Near Earth Space Signatures

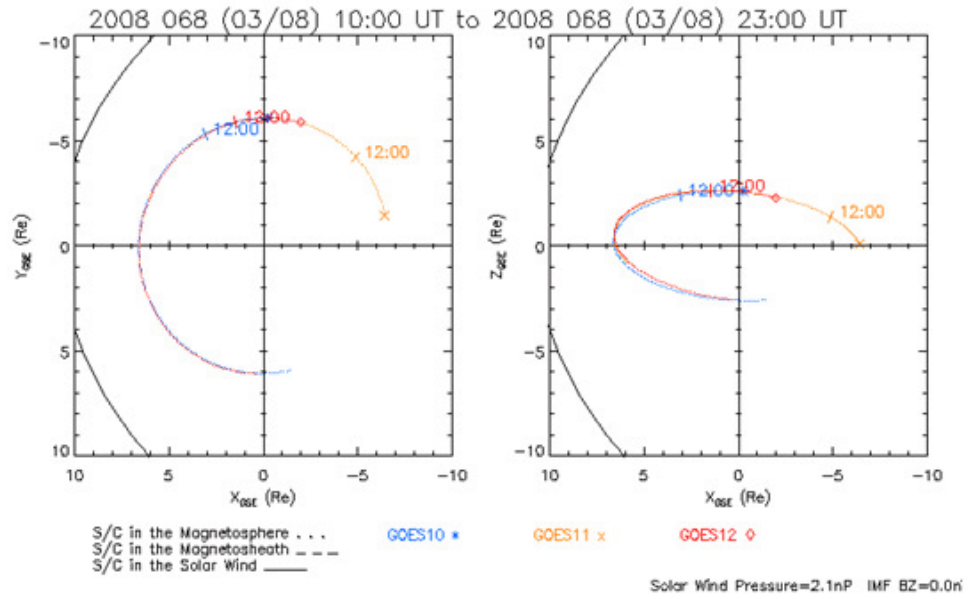


Figure 4.21: Trajectory of GOES satellites

GOES satellite positions are plotted in Figure 4.21. NASA Satellite Situation Center was used for this purpose. GOES 10, 11, and 12 positions are given in the plot. GOES 11 was at the nightside approximately until 14:00 UT, and GOES 11 was at the dawn sector. Therefore their positions were more useful for this study than GOES12 which moved to dayside during our events.

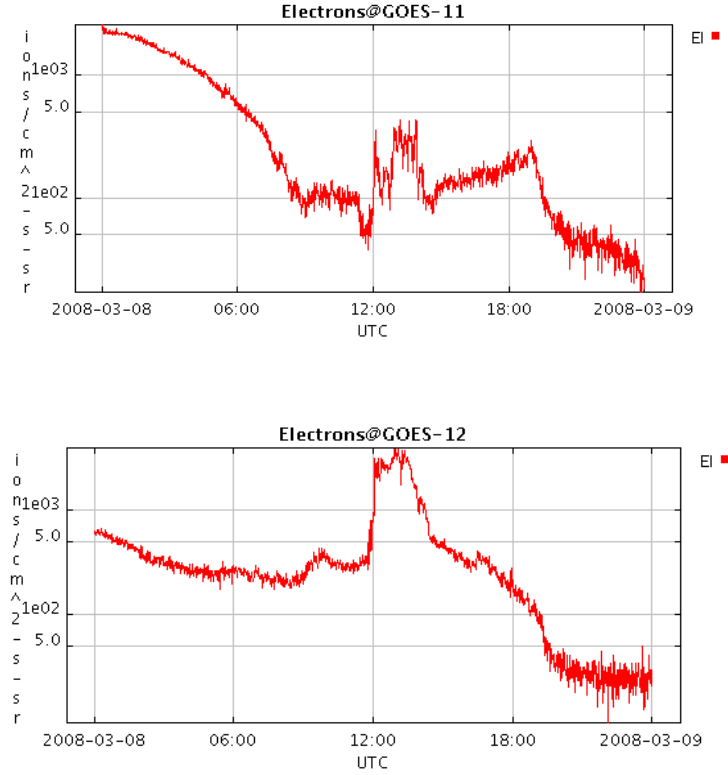


Figure 4.22: GOES satellite electron flux measurements

GOES satellites have a particle detector on themselves. In Figure 4.22, the electron flux measurements taken from GOES11 and GOES12 are shown. Both satellites observed an increased number of incoming electrons during the first substorm as they were both in the nightside magnetosphere. Observed electron flux increased at 12:15 UT, 13:00 UT, and 14:20 UT. These electron flux enhancements correspond to the BBFs which were observed by ThD, ThE and ThC. By considering the dipolarizations seen at the time of these BBF events, we relate these electron flux enhancements to the BBFs, but more analysis is needed to conclude this.

4.7 Ionospheric Convection

Blue and red areas represent the potentials in Figure 4.23. Colored vectors are the observed drift velocity vectors by SuperDARN. As illustrated, two cell convection patterns were apparent for both substorms, and the ions drifting from dayside to nightside are easily detected. Convection spreads to lower latitudes in second substorm.

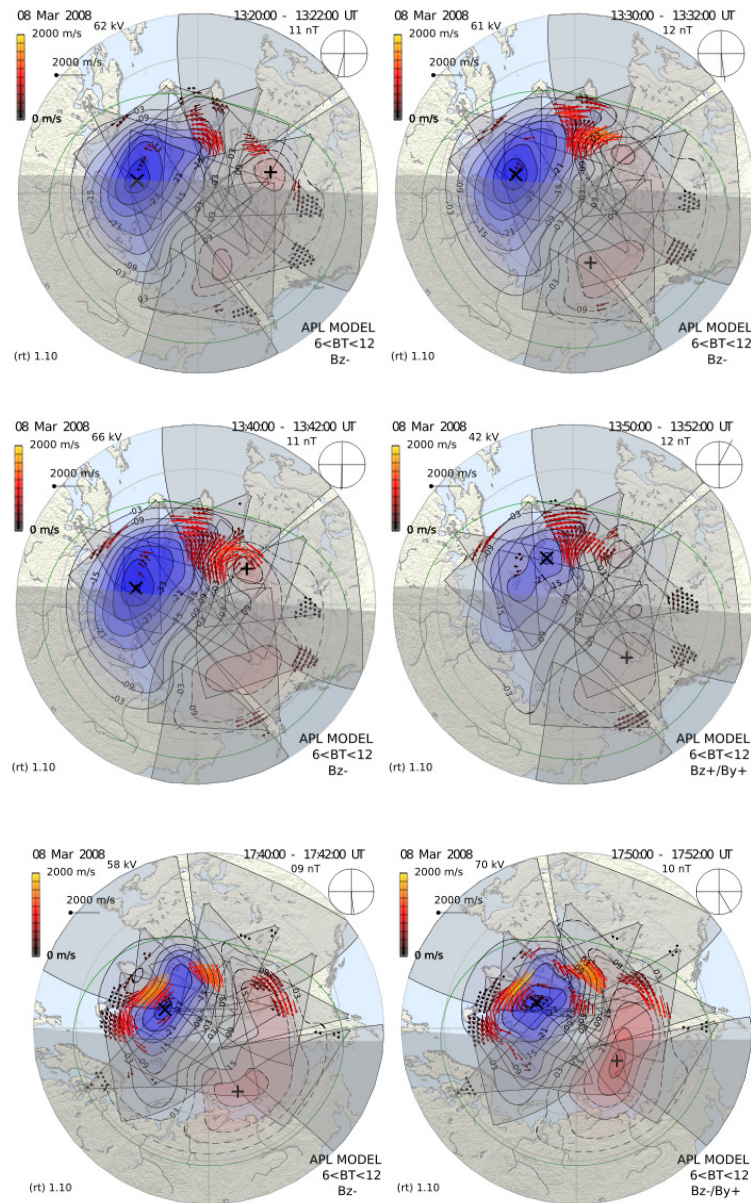


Figure 4.23: Convection patterns during the first and second substorm

4.8 Energy Budget and Joule Heating

Figure 4.24 gives the solar wind energy input into the magnetosphere as measured by the epsilon parameter, IMF B_z, and the resultant auroral electrojets as depicted by AU (red) and AL (red) indices. Epsilon parameter signifying the energy transfer to magnetosphere was calculated using Formula 1.1 given in subsection 1.4 in the first chapter, using solar wind parameters from Wind spacecraft. Epsilon dependence on IMF B_z is clearly seen with increased epsilon values being associated with southward IMF B_z periods. There were two intervals with increased epsilon values and each corresponding to the substorm times indicating that the magnetosphere is being loaded. Blue lines mark the onset times. AU and AL indices show a lag of thirty minutes from epsilon parameter increase for the first substorm till the first substorm onset. The energy deposition was seen to start half an hour earlier than the ionospheric activity and 15 min. later than the southward turning of IMF B_z. For the second substorm the time lag between epsilon rise and the onset as seen in AE index was about 45 minutes whereas the time lag between IMF B_z and AE was about 20 minutes. The time lag between the response of ionosphere and energy deposition in both events suggest loading and unloading mechanism as the dominant mechanism for these substorms.

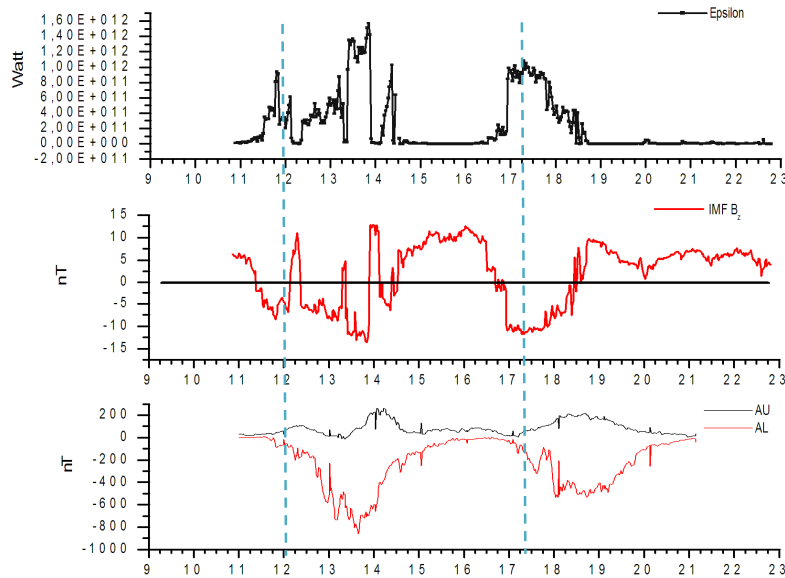


Figure 4.24: Epsilon, IMF B_z and Auroral Electrojet indices for March 8, 2008

The energy input to magnetosphere was dissipated in several channels. As events on March 8, 2008 were isolated substorm events, and ring current gains importance in large disturbances like geomagnetic storms, ring current injection was omitted and not calculated, and most of the contribution was assumed to be coming from auroral particle precipitation and Joule heating components in the ionosphere. Palmroth et al. claimed, in total, Joule heating dissipation in both hemispheres corresponded to 50-60% of the transferred energy during isolated substorm events and 50% during storm time events (2005, and references therein).

Joule heating was calculated using several methods. One method was to calculate using AE index, using the formula which was given by Ahn et al. (1989) in Chapter 1, subsection 1.4, Figure 1.6., for 12 stations and summer season. Although, the events studied here occurred in March (spring), this value was also used in Ostgaard's study (2002) for a March substorm and proved to be appropriate. The results were plotted in panel a of Figure 25.

Another method using a different index is using the IL index which is derived from Scandinavian chain magnetometer records. It was multiplied by the constant given by Tanskanen(2002) which is $3 \cdot 10^8$ and the resulting joule heating is shown in

panel b of Figure 4.25. Between 16:00 UT and 02:00 UT IMAGE magnetometer chain is in the midnight sector so it gives a good approximation to global AL index as reported by Tanskanen (2002) .

We also used electric field values at AE stations derived from SuperDARN radar network measurements to calculate the joule heating as there are more physics in the electric field measurements and the radar responds to the line-of-site scattering of the particles at the ionospheric levels, and gives the electric field potentials and drifting velocities. To obtain the joule heating, the electric field data were used with IRI2007 Pedersen conductivities in the formula (1.5), subsection 1.4 of Chapter 1. IRI2007 gives local, hourly, mean conductivity values while electric field measurements from SuperDARN are in 10 minutes resolution. For the calculation of Joule Heating this average conductivity was multiplied by every electric field value at that hour. Results of this calculation are plotted in Figure 4.25 panel c.

Lastly, joule heating results obtained from BATSRUS model run were plotted in Figure 25 panel d. BATSRUS model calculates joule heating (JH) using field aligned currents (FACs) that are taken from the global magnetosphere module with (4.1). JH dissipation rate is given by the Ionospheric Electrodynamics module.

Solar radio flux F10.7 was 68.8 for March 8 and ionospheric conductance was calculated using semi-empirical auroral conductivity component.

$$W_{diss} = \frac{j^2}{\Sigma_p} \quad (4.1)$$

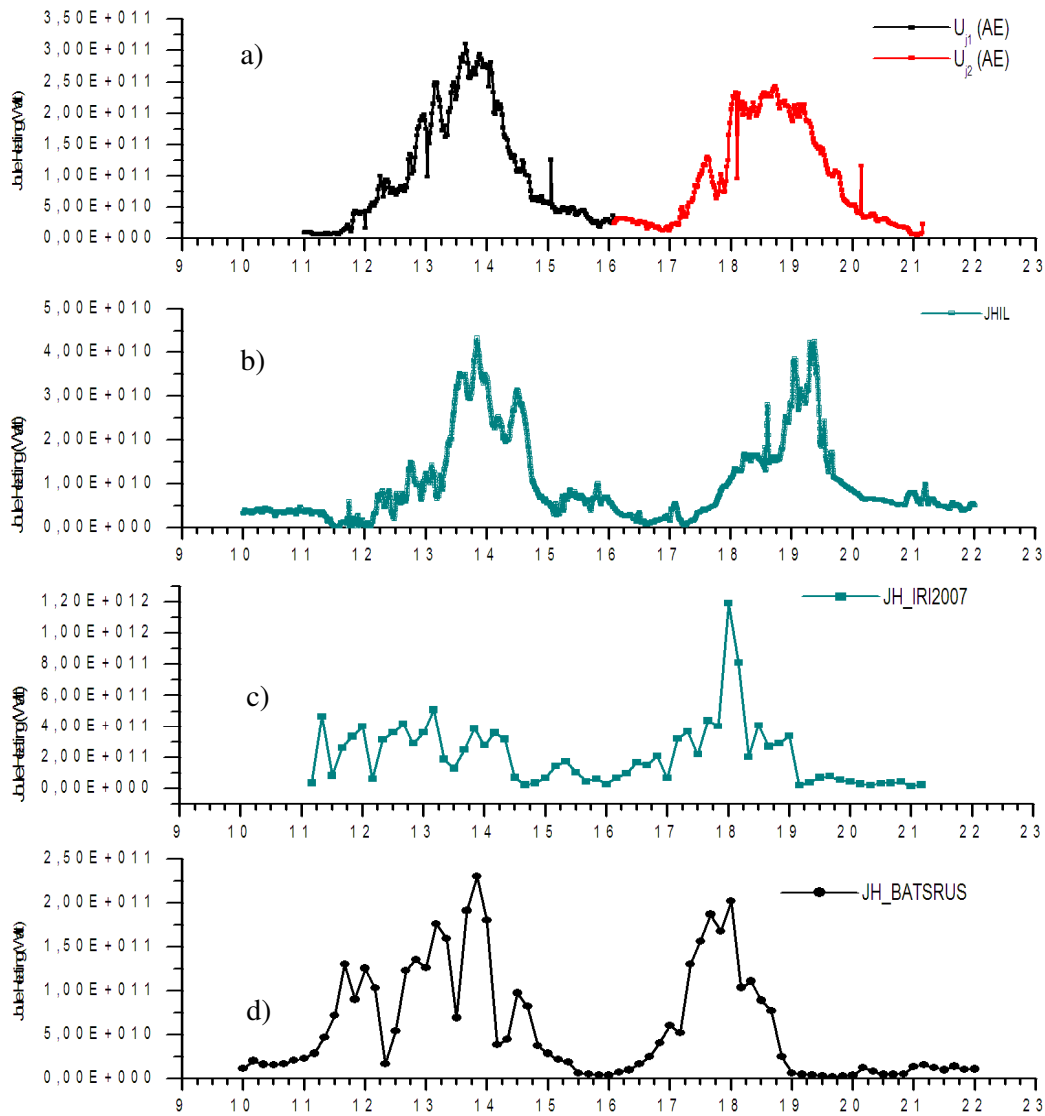


Figure 4.25: Joule Heating values on March 8, 2008 by different methods

Figure 4.25 illustrates the resulting calculations of Joule Heating dissipation in the upper atmosphere. In general, all three methods used to calculate the joule heating is seen to give close variations during the course of the both substorms. Maximum values are found in panel a of AE index estimation of Joule heating. Among the three, SuperDARN+IRI2007 combination gave an exceptionally high JH peak rate (JH_IRI2007) during the second substorm which was on the order of 1.2×10^{12} Watt. This will be discussed in the next section of the thesis. The lowest estimation of joule heating came from the IL index calculation with estimated values on the order of 1×10^{10} Watt all substorm times. On the other hand, except the peak in the second substorm JH_IRI2007, JH_BATSRUS and JH_AE were all in the same order of magnitude. JH rate estimates from BATSRUS were nearly the half of AE index calculated values. This underestimation might come from the underestimation of the FACs in the model or the assumption used in different modules related to the joule heating may not reflect the ionospheric conditions well. There can also be an overestimation in AE values due to the season as given in Ostgaard(2002).

In Figure 4.25, JH_BATSRUS is seen to respond to the energy deposition or to the southward turning of the IMF Bz half an hour earlier than the AE index. This is also the case we see in JH_IRI2007. The joule heating rate in both of these methods also ends half an hour earlier than that in AE method. Although the order of magnitudes in IL method results is much lower than those of AE method, the general tendency of catching the general features, including the timing of the joule heating peaks, is seen to be similar to other methods considered. JH_IRI2007 didn't increase significantly in magnitude during the first substorm. Rather, it fluctuated around 3×10^{11} Watt while other calculations showed JH increase with a strengthening of the electrojet during expansion phase. To understand the sharp increase in JH_IRI2007 rate, which on the order of 1×10^{12} Watt, seen at about 18:00 UT in panel c of Figure 4.25, we plotted hourly Pedersen conductivity and electric field obtained from SuperDARN measurements. This is shown in Figure 4.26.

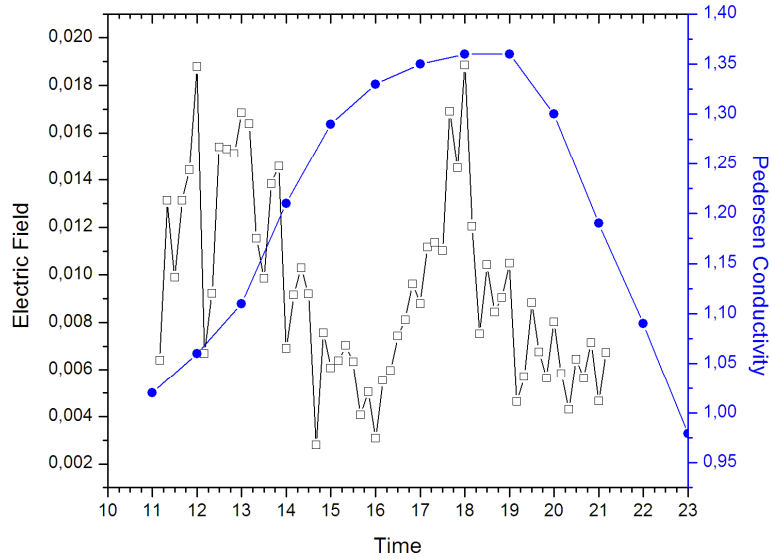


Figure 4.26: Electric field (mV/m) and Pedersen conductivity (S/m) vs. time

In Figure 4.26, we can see that there wasn't any abrupt increase in average electric field at 18:00 UT. However, the peak of the Pedersen conductivity is seen to overlap with E giving rise to higher joule heating rates in the upper atmosphere. In spite of the fact that JH_IRI2007 mostly follows electric field variations, this overlapping led to an overestimation in the SuperDARN based joule heating calculations. The increase in the Pedersen conductivity at about 18:00 UT from IRI2007 is, on the other hand, another parameter calculated in IRI models based on the assumptions. It does not take the effect of the auroral activations or the precipitating electrons into account which will contribute to the conductivity. The peak in conductivity seen at 18:00 UT is thus not clear why the conductivity shows a rise at 18:00 UT and will be explored later in detail.



Figure 4.27: SuperDARN radar network and AE station locations

In Figure 4.27, SuperDARN and AE station locations were plotted together. Red points show the location of SuperDARN radars while blue points give the location of AE stations. AE stations are seen to be uniformly distributed around the northern polar cap regions while there is a gap in the SuperDARN network coverage seen at the bottom left of Figure 4.27. For the estimation of Joule Heating using AE index, this could cause an underestimation of the strength of the auroral electrojet at that sector as compared to the AE index, thus may result in lower values of joule heating rates overall for that substorm. In that case, there would be a reduction in the electrojet signal even though the disturbance was much effective, but this doesn't show that AE index based method would give Joule heating rates in the order of 10^{12} Watt.

Spatial variations of JH rates in the upper atmosphere from BATSRUS taken at different snapshots corresponding to the 11:00UT, 12:10 UT, 15:00UT, 18:00UT, 20:00 UT in Figure 4.25 corresponding to start, onset, end of expansion and mid-recovery times of substorms are presented in Figure 4.28.

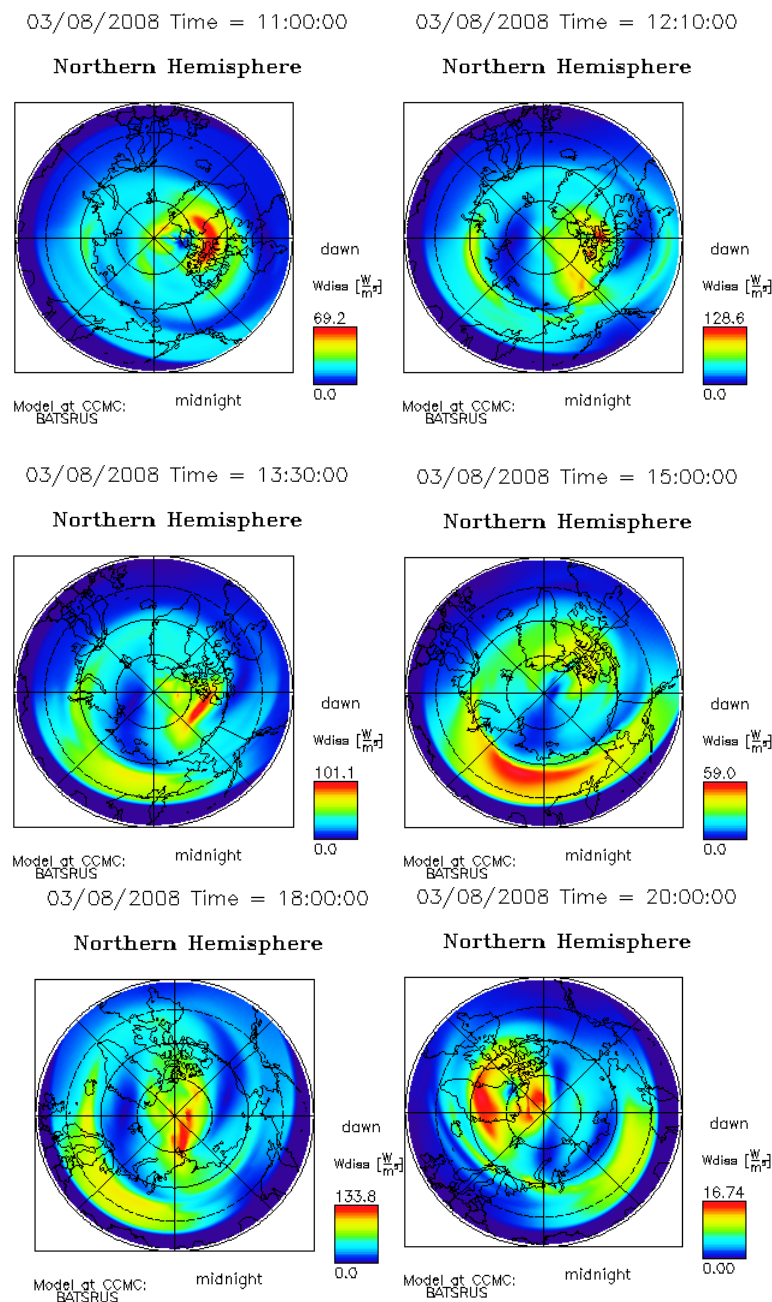


Figure 4.28: Spatial JH variation

Maximum JH was found mostly in the polar cap region at the start of the first substorm at 11:00 UT, and is denoted by the color scale in the right of the figure.

The values are seen to be about 69.2 W/m^2 on the dawn side. With the onset at 12:10 UT, JH values started to increase and move equatorward to lower latitudes and at about 13:30 UT stronger dissipation rates appeared in a broader region between dusk and midnight which was the end of expansion phase. Although at 15:00 UT JH exists in a larger area, looking at the color scale, we can say that the values are not as big as those of the expansion phase. The sequence was similar in the second substorm. At the strongest electrojet time and end of the expansion phase, the largest JH values were found between midnight and dusk sectors, and Joule heating ceased with the recovery.

5. SUMMARY AND FUTURE WORK

In this study, we have examined two consecutive magnetospheric substorm events and determined the Joule heating rates in the upper atmosphere during these events. Magnetospheric substorms are important as they supply the mechanisms through which the solar wind energy and momentum are transferred into the upper atmosphere at the ionospheric heights. The energy and the momentum flow is controlled by the solar wind power impinging on the dayside magnetopause and the internal dynamics of the magnetotail where this power has been deposited through the open field lines of the magnetotail. Internal dynamics of the magnetotail especially plays a crucial role in distributing solar wind energy into the upper atmosphere. Specifically, this study investigates the comparability of the methods which are used to calculate the upper atmospheric Joule heating for the purpose of bringing the differences out and gaining insights on the physics and the dynamics behind these differences. The physical processes and tail dynamics that lead to the auroral precipitation and Joule heating in the upper atmosphere are mainly regulated by the processes inherent to the magnetotail and to a lesser degree locally in the ionosphere. Therefore, we demonstrate and analyze the magnetic field and plasma variations in the magnetotail and in the solar wind which give rise to the Joule heating we observe in the upper atmosphere during these substorms as well as investigating the characteristics of the substorms. We used data from TH, GOES and WIND spacecraft in the magnetotail, near-Earth tail and in the solar wind, data from SuperDARN radar network in the ionosphere, data from the ground magnetometer stations and data from global magnetohydrodynamic model BATSRUS at CCMC in order to infer to the changes and processes in the different regions. We searched for substorm events in THEMIS data for about three months and found four substorms event. Here we have chosen to present the March 8, 2008 substorm events which were especially chosen as they offer a complete data set in different domains of the magnetospheric environment.

The solar wind drivers, ground and ionospheric responses, and magnetotail processes were presented in a coherent manner in order to understand the differences in the Joule heating calculations between the various methods. We can summarize our findings as below:

- 1) Both substorms occurred in March 8, 2008 were identified as isolated substorms as Dst magnitude was less than 40 nT.
- 2) AL is measured to be stronger than -1000 nT. The response of AE and ground signatures showed a time lag of at least 30 minutes from the increase in the solar wind power, measured by epsilon parameter, at the magnetopause. This implies that the energy from the magnetosphere, where it is deposited, to the ionosphere, where it is dissipated, has been delayed by about half an hour. This is an indicative of the loading-unloading processes in the magnetotail during our events.
- 3) Magnetotail flows using THEMIS spacecraft data were often detected to be related to changes in the direction of the IMF Bz. We see that both the fast earthward and tailward flows are often found to be associated with northward IMF Bz.
- 4) In general, tailward and earthward flows were seen by several THEMIS spacecraft indicating tail reconnection occurred somewhere around -11.7 Re. Tailward flows were seen to be preceded by earthward flows frequently. Most of the tail flow enhancements occurred during the expansion phase of the first substorm which is in agreement with the findings of earlier studies. However, we observe most of the fast flows during the recovery phase of the second substorm.
- 5) Our preliminary search based on these substorm events does not suggest an influence of solar wind dynamic pressure on the tail flow direction or strength. Most of the earthward and tailward fast flows were observed around -9 Re. Therefore this suggests that the acceleration region is in Near Earth tail.

- 6) Dipolarizations of the magnetotail field is often found to accompany the earthward and tailward fast flows in the center of the tail which further implies a reconnection region at the near Earth tail region. Table 5.1 gives the properties of magnetotail flow maximums during the substorms. In the table, N means northward, S means southward, whereas upward pointing arrows denote the increase and downward arrows denote the decrease in the quantity.

Table 5.1: Summary of Magnetotail Flows

Space craft	Time (UT)	Distance (Re)	Vx max (km/sec)	Vx_max Direction	Tail Bz (nT)	IMF Bz (nT)	Phase
ThB	19:20	24	520	Earthward	↑	N ↑	recovery
ThC	14:23	14.8	500	Earthward	↑	S ↓	recovery
ThD	12:15	9	550	Earthward	↑	N ↑	expansion
ThE	13:02	9	600	Earthward	↑	S ↓	expansion

- 7) We observe increased amount of energetic electrons at geostationary orbit during our substorm events. GOES spacecraft particle injection observations showed increased number of particles corresponding to the times when we observe earthward and tailward fast flows. This observation was also supported by the observations of Sergeev (2004).
- 8) SuperDARN radar network convection maps displayed high convection rates and particles drifting from dayside to nightside with clear two cell convection pattern occurring during the southward IMF Bz conditions.
- 9) The highest Joule Heating rates are found using AE index except the SuperDARN result during the second substorm. IL index based Joule heating calculation gave the lowest rates because this index is just a local index covering only limited number of stations at the Scandinavian sector. The BATSRUS simulation and SuperDARN results gave closer Joule heating rates to those calculated using AE index but with about half an hour early appearance of the peak in Joule heating. SuperDARN-IRI2007 method

overestimates the Joule heating in the second substorm. This overestimation seems to be associated with the coinciding increase in the conductivity with the electric field at 18:00 UT of expansion phase of the second substorm. The reason why conductivity increases at 18:00 UT in IRI2007 model remains to be investigated. The summary of the calculated Joule heating values are given in the table 5.2 below.

Table 5.2: Joule heating results for March 8, 2008 substorms

Method	Order of Magnitude (Watt)	Peaks and Trends	Timings
Index Based Method	AE: 1×10^{11} IL: 1×10^{10}	AE-IL trends similar	Timings match
SuperDARN- IRI2007	1st substorm: 10^{11} 2nd substorm: 10^{11} except the peak	Have a peak of 10^{12} doesn't match with other methods	Half an hour earlier than index based methods
BATSRUS	Order of magnitude is the same as AE index based method, but gives values approximately half of JH_{AE}	Trends are the same with index based methods	Half an hour earlier than index based methods

10) The classical and the most often used way of calculating the Joule heating is the AE index based method. In this study our purpose was to compare the results from different methods and reveal the places where they are weak and need to be improved. To fulfill this purpose, we applied three methods: AE index base, SuperDARN radar data, and BATSRUS MHD model data. As AE index is statistically determined, it does not bear any physics in it. As for the BATSRUS MHD model, it allows us to investigate the Joule heating for a range of solar wind conditions and the changes in 3D and in detail in different associated regions where we have limited access. We can also learn and

investigate deeply on the physical and dynamical processes using the model. However, the model also has its own disadvantages as they are based on several assumptions in determination of the Joule heating as it involves several modules. The differences in the results of SuperDARN radar network in combination with IRI2007 conductivities may result from the estimates of the conductivity which are known to be underestimated in IRI based models (personal communication with M. J. Ruohoniemi, 2009). The radar operates on line-of-sight basis and uses the scattering from the particles only along the path of the radar beam. Thus the electric fields computed at the ionospheric heights might be underestimated which can then affect the Joule heating calculations. This study will be extended to several substorm events to drive physical conclusions behind the differences we have obtained in this case study and explore more on the physics and dynamics of the regions that eventually lead to the Joule heating in the upper atmosphere. As in all time pressured studies, we did not have time to extend it to drive specific conclusions in this version. Our papers based on the case study presented here will include the extended version.

- 11) One last method we have not tried but we would like to is to try to estimate the Joule heating using parallel currents (FACs) based on the simultaneous measurements of THEMIS and a LEO orbiting spacecraft. Calculating Joule heating using Poynting flux and FACs will present more physical insights in our calculations and would give us directly comparable results with the model. Here we have not yet address on the model assumptions and weaknesses but our future study will be towards the testing and validating the model in great detail and revealing the weaknesses by comparing it with the observational results.
- 12) The timing of the magnetotail fast flows and the maximum Joule heating coincides very well in our preliminary results based on these two substorm cases. We would like to extend our case studies to quantify these findings as well.

13) Another point which has been neglected in this study is the role of the thermosphere and the neutral winds in the upper atmosphere which can have influence in electric fields. The problem at this point is that there are no simultaneous measurements of neutral wind and electric fields to include these in the Joule heating calculations.

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1-) Kalafatoglu E.C., Z. Kaymaz, Joule Heating Comparisons: A qualitative study of models, statistical methods and observations, *to be submitted to GRL*.

2-) Kalafatoglu, E. C. And Z. Kaymaz, Solar Eclipse and Meteorological Effects: A statistical study of August 11 Turkish Eclipse, to be submitted to *Journal of Atmospheric and Solar Terrestrial Physics*.

3-) Kalafatoglu E.C, Kauristie, K., Partamies, N., THEMIS Observations of December 31, 2007 Substorm Event, *to be Submitted to Geophysica*

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