STUDY OF SUB-AURORAL DYNAMICS USING INTEGRATED MEASUREMENTS

A THESIS

SUBMITTED TO THE UNIVERSITY OF MUMBAI FOR THE Ph.D. (SCIENCE) DEGREE IN PHYSICS

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UNDER THE GUIDANCE OF DR. ASHWINI KUMAR SINHA

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APRIL 2016
Dedicated to Maa Baba and Muna...
STATEMENT BY THE CANDIDATE

As required by the University Ordinances 770, I wish to state that the work embodied in this thesis titled “Study of sub-auroral dynamics using integrated measurements” forms my own contribution to the research work carried out under the guidance of Dr. Ashwini Kumar Sinha at the Indian Institute of Geomagnetism, New Panvel, Navi Mumbai. This work has not been submitted for any other degree of this or any other University. Wherever references have been made to previous works of others, it has been clearly indicated as such and included in the Bibliography.

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Certified by

Signature of Guide

Name: Dr. Ashwini Kumar Sinha
Statement required under 0.770

I hereby declare that the work described in the thesis has not been submitted previously to this or any other University for Ph.D or any other degree.

Statement required under 0.771

“Whether the work is based on the discovery of new facts by the candidate or of new relations of facts observed by others, and how the work tends to the general advancement of knowledge”.

The first chapter provides basics of the thesis work by introducing solar terrestrial environment and important geomagnetic activities. Motivation behind this thesis has also discussed in brief. In the following chapters, the original work done by the candidate is described. This includes the validation of the new Imaging Riometer data set, event based study and statistical study of some new observations with the help of new Imaging Riometer data set at Maitri, Antarctica. Processes such as substorm related cosmic noise absorption and their relations to interplanetary conditions, features and uniqueness of day side cna (DCNA), modulation of particle precipitation due to geomagnetic pulsations were thoroughly studied. In the final chapter, the results are summarized and scope for future work is discussed.

New findings from the work are listed below:

• This thesis is essentially first of its kind to elaborate the facility, data processing, validation as well as applicability of Indian first Imaging Riometer installed at Maitri, Antarctica. Addition to it, the importance of location subject to space weather activities for carrying out
the study which is further discussed. Therefore this thesis initiates a new tool for the upper atmospheric study from a remotely situated sub-auroral location such as Maitri.

- This thesis has fairly differentiated the spatial and temporal characteristics of cosmic noise absorption (CNA) events occur during different geomagnetic activities. It also showed that the level of CNAs depend upon the level of activities and type of activities. Here, geophysical activity such as auroral substorm, geomagnetic strom, solar flares were mainly taken into consideration. LT distribution of CNA event occurrences at Maitri show off more pronounce during dawn hours (38%). Almost same amount of occurrences (∼23%) have been seen during day and night sector. Occurrences of CNA events are seen least in the dusk sector. This result is very much in agreement with the previous studies done by Kavanagh et al. in 2002, 2012. Additionally, Preliminary study of substorm induced CNA at Maitri has revealed that the CNA production during the storm-time substorm are larger than those during isolated substorms. Also, it can be seen that the CNA production depends on individual interplanetary parameters such as $IMFBz$, solar wind velocity ($Vs$).

- Statistically, auroral Substorm related CNA are found to occur during post local magnetic mid night hours (∼0200 MLT) at Maitri. These auroral substorm CNA were seen to have simultaneous occurrences of negative bay or, intensification of westward electrojet and the production of CNA at the same location. These events were essentially driven by field align precipitation of softer KeV electrons. Relation of these events were statically analyzed in the light of interplanetary parameters mainly IMF Bz and Solar wind velocity ($Vs$) and dusk ward interplanetary electric field ($IEFEy$). Contrast to many previous works, it is seen that CNA related to auroral substorms are highly dependent on the $IEFEy$ in stead of individual interplanetary parameters.

- CNA events are produced not only due to Precipitation of energetic electrons through open field lines but also from the trapped electrons from the closed field lines. This thesis has reported, for the first time, various characteristics of day side cosmic noise absorption (DCNA) events at Maitri. It has described the necessary and sufficient conditions for the
occurrences of such events. It explained that DCNAs are precisely produced due loss cone scattering of sub-relativistic electrons ($\sim 100s$ of KeV electrons) that drift in the equatorial plane. A comparison has been made between the DCNA event of 02 April 2011 with that of 14 July 2011, a day with substorm activity when Maitri is in day side but without DCNA event. The study shows that stronger prolonged eastward interplanetary electric field favors the occurrence of DCNA event. Estimated energy of trapped electrons using azimuthal drift time for a set of ground stations within the auroral oval confirms the enhancement in electron fluxes in the same energy band as recorded by geostationary satellites GOES 13 and GOES 15. The reason for precipitation of electrons is expected to be the loss cone scattering caused by wave-particle interaction triggered by ULF waves.

- This thesis has also studied the high latitude impact of the largest geomagnetic storm since the beginning of the current solar cycle (solar cycle 24). The sudden storm commencement of this severe geomagnetic storm (level G4) has been observed at 0445 UT on 17 March, 2015. The SYM-H index reached two local minima of -93 and -150 nT at 0940 and 1630 UT, respectively. Though the production of CNA is pronounced during the main phase of the storm, the CNA enhancement during the first day of recovery phase, particularly 14-17 MLT at Maitri is more larger. The CNA pattern exhibits oscillation in the Pc5 range and is in simultaneity with geomagnetic pulsations during the same hours. It is found that the intense CNA production is mainly due to hiss-driven sub-relativistic electrons. Absence of EMIC (Electro-magnetic Ion-cyclotron) waves is marked which confirm the role of VLF waves in causing precipitation. Additionally, signature of enhanced eastward electrojet at Maitri during 14-17 MLT at Maitri could be an additional factor for such large CNA. Further, The spatial characteristics of Pc5 waves during the CNA event were critically examined using IMAGE chain magnetometers.

- Effort has been made to understand the solar flare effect on the riometer signal. It is known that X-ray can produce ionization in the D-region of the Ionosphere. However, the analysis sees no effect in the riometer signal at maitre which is operated at 38.2 MHz. The
reason of no alteration of the riometer signal is attributed to the lack of threshold D-region ionization, reduced collision frequency compared to low latitude and high operating frequency of the riometer. Theoretical explanation has also been provided to explain the observation.
Statement required under 0.771 Statement No. 3

"The source from which this information has been derived and to the extent to which he has based his work on the work of others, and shall indicate which portion or portions of his thesis he claims as original”.

The information mentioned is derived by the candidate during the course of research work which is reported in the thesis. Some of the results presented in the thesis are published in the following research articles:

- **Papers Published in Journals**


  (3) **Jayanta K. Behera**, Ashwini K. Sinha, Geeta Vichare, Olga Kozyreva, Rahul Rawat and Ajay Dhar, Day side cosmic noise absorption at the equator-ward boundary of aurora oval as observed from Maitri, Antarctica (L=5; CGM 62.45° S, 55.45° E), JGR space physics (accepted), 2016.

- **Papers under preparations**

  (4) **Jayanta K. Behera** et. al., Modulation of precipitated particles at high latitude during
the recovery phase of 17th April, 2015 geomagnetic storm, Manuscript is under preparation, 2016.

(5) Jayanta K. Behera et. al., Observations of solar Flares in imaging RIometer signal of 38.2 MHz at Maitri Antarctica, Manuscript is under preparation, 2016.

• Technical Publications
  
   (1) Jayanta K. Behera, Ashwini K. Sinha, Ajay Dhar and K. Jeeva ; Technical descriptions of narrow beam and wide beam application of imaging riometer to study energetic particle precipitation (Submitted to Ministry of Earth Science Dept.).
  
   (2) Jayanta K. Behera, Ashwini K. Sinha, Anand K. SIngh Ajay Dhar; Observations of different kind of cosmic noise absorption (CNA) events at sub-auroral latitude (submitted Ministry of Earth Science Dept.).
  
  
  
• Papers presented in National and International Conferences

(2) **Jayanta K. Behera**, Ashwini K. Sinha, B. M. Pathan, Rahul Rawat and Anand K. Singh; Statistical relations among substorm occurrence, geomagnetic pulsations and particle precipitation pulsations as seen at Indian Antarctic station Maitri, COSPAR, July 14-22, 2012, Mysore, India.

(3) **Jayanta K. Behera**, Ashwini K. Sinha, B.M. Pathan, R. Rawat, Anand K. Singh; Seasonal influence of cosmic radio noise signal at Indian Antarctic station Maitri, ISSTP, November 6-9, 2012, Pune, India.


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(1) Winter member of XXXIII Indian Scientific Expedition to Antarctica, December 2013-January 2015

(2) YOUTHSAT Workshop on data utilization for Ionosperic study and hands-on training, 14-15 October, SPL, Vikram Sarabhai space Centre (VSSC), Trivendrum, Kerala, 2011.
“Where a candidate presents joint work, he shall clearly state the portion which is his own contribution as distinguished from the portion contributed by his collaborators.”

The analysis and formulation of the problems attempted in this thesis were carried out by the candidate. Dr. Ashwini K. Sinha is the guiding teacher and has helped in formulating the problems as well as provided guidance throughout the course of the work. Dr. Ashwini K. Sinha, Dr. Anand K. Singh and Dr. Geeta Vichare have contributed towards the interpretation of results and helped in the preparation of manuscripts as mentioned in Statement No. 3. Rahul Rawat has helped in computational works. During different expeditions to Indian Antarctic station Maitri, Riometer and Magnetometer data were collected by the Institute’s scientific staffs Mr. Ajay Dhar, Mr. K.U. Nair, Mr. C. Selvaraj, Mr. P. Elango, Mr. Sachin Labde and Mr. K. Jeeva.

(Dr. Ashwini Kumar Sinha)  
Guiding Teacher

(Jayanta Kumar Behera)  
Candidate
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I can recollect the chronicle of my Ph.D. tenure at IIG in a flash. Undoubtedly, this is my longest association with any institution for a degree. As Sir Isaac Newton once said 'if I have seen further it is by standing on the shoulders of giants’. No dreams can be achieved without the help of a collection of people. I owe my deepest thanks to such people.

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Jayanta Kumar Behera

Candidate
# Contents

Statement ......................................................... iv  

Acknowledgements ........................................... xiii  

1 Introduction .................................................. 1  

1.1 The solar terrestrial Environment ......................... 1  

1.2 Earth’s Magnetic field and its components ............... 6  
   1.2.1 Geomagnetic Field components ...................... 10  

1.3 Earth’s Magnetosphere .................................. 11  
   1.3.1 Motion of charge particles in side the Magnetosphere 16  
   1.3.2 Current system in Magnetosphere .................. 17  
   1.3.3 Particle precipitation processes ................... 20  

1.4 Ionosphere ............................................... 21  
   1.4.1 High latitude ionosphere ......................... 22  
   1.4.2 Radio wave absorption in ionopshere ............... 25  

xvi
1.5 Solar wind Magnetosphere- Ionosphere system

1.5.1 Geomagnetic storms

1.5.2 Magnetospheric substorm

1.5.3 Geomagnetic pulsations

1.6 Indices

1.6.1 Auroral Indices (AU, AL, AO and AE)

1.6.2 $Dst$, $SYM − H/D$ and $ASY − H/D$

1.6.3 Wp-index

1.6.4 $K$, $Kp$, and $ap$

1.7 Scope of the thesis

2 New imaging Riometer at Maitri, Antarctica

2.1 Introduction

2.1.1 Indian perspective of Ionospheric study using Cosmic Noise Measurements

2.1.2 The principles of cosmic noise absorption process

2.1.3 Advantages and essential features of an imaging Riometer

2.1.4 Installation of imaging Riometer at Maitri

2.1.5 Importance of operating frequency of imaging Riometer

2.2 Quiet day curve and validation of imaging Riometer data set
2.2.1 Technique for deriving QDC ........................................ 59
2.2.2 Sidereal time and Monthly variation of QDC at Maitri, Antarctica 61
2.3 Initial observations ....................................................... 65
  2.3.1 Data sets ............................................................ 69
  2.3.2 Keograms for different geomagnetic activities ................. 69
  2.3.3 LT distribution of CNA events at Maitri ....................... 76
2.4 Discussion and Conclusion ............................................. 77

3 Substorm related CNA at Maitri 81
  3.1 Introduction .......................................................... 81
  3.2 Data sets and event selection ...................................... 84
  3.3 Observations .......................................................... 85
    3.3.1 Event of 20 April 2011 ......................................... 85
    3.3.2 Event of 9 August 2011 ....................................... 87
    3.3.3 Event of 29 May 2011 ....................................... 87
  3.4 Statistics of substorm related CNA events ....................... 90
    3.4.1 MLT dependence of the events ............................... 90
    3.4.2 Substorm onset, westward electrojet onset and CNA onset .. 91
    3.4.3 Effect of interplanetary conditions on CNAs .................. 92
  3.5 Results and discussion .............................................. 94
  3.6 concluding remarks .................................................. 95
4 Day side CNA (DCNA) and wave-particle interaction

4.1 Introduction ................................................................. 97
4.2 Data sets ................................................................. 100
4.3 Observations .............................................................. 102
  4.3.1 A day side absorption event with interplanetary conditions .... 102
  4.3.2 A day side no-absorption event with similar Interplanetary conditions 108
  4.3.3 GOES-13 observation during both the event ....................... 108
4.4 Global Pc5 (2-7 mHz) waves observed with DCNA .................. 113
4.5 Discussion .............................................................. 116
4.6 Conclusions .............................................................. 126

5 CNA response to the recovery phase of 2015 St. Patrick’s day geomagnetic storm 128

5.1 Introduction .............................................................. 128
5.2 Data set ................................................................. 131
5.3 Observations .............................................................. 132
  5.3.1 17th March geomagnetic storm event ............................... 132
  5.3.2 Observation at Maitri during storm .................................. 135
  5.3.3 Latitudinal and longitudinal IMAGE chain observations ........ 140
  5.3.4 Magnitude-squared coherence and cross spectrum phase ......... 143
5.4 Discussion .............................................................. 144
5.5 Conclusions .............................................................. 149
6 Conclusions and future work 151

6.1 Scope of future work 154

Bibliography 156

Synopsis 1
Chapter 1

Introduction

1.1 The solar terrestrial Environment

Principally, solar terrestrial environment is manifested by the interaction of energetic charged particles, mostly deriving their energy mostly from the sun, with the electric and magnetic field in space. Sometimes, charge particles feed on the energy released during the interaction of solar wind and the magnetosphere. However, these phenomena are very complex, because the electromagnetic field which determines the trajectories of the charge particles is also affected by the charge particle’s motions. Additionally, state of these charge particle and the geometry of Earth’s magnetic field lines make the situation more complicated for the Solar-terrestrial research community. The emerging field of Solar-terrestrial began with the appreciation of couple of events, firstly the popular sighting of Aurora which is mentioned in Greek literature in sixth century B.C. and in Chinese literature prior to 2000 B.C. and secondly, the geomagnetic field variations linked to the auroral observations[Kivelson and Russell].
CHAPTER 1. Introduction

Figure 1.1: Structure of Sun

Sun, Solar wind and Interplanetary parameters

The supreme cause of the terrestrial interaction is the Sun, a middle aged with $G2V$ spectral type star and is very familiar to Astronomers. But, while dealing with space weather activities and their geo-effectiveness, Sun gets full attention from the space research community. At first glance, Sun interact with the Earth through various processes such as radiative, dynamic and magnetic processes. This thesis in general studies the geo-effectiveness of these interactions. Some of the facts about the Sun have been mentioned here. Sun’s mass is $330,000$ times larger and radius is $109$ bigger than Earth. One astronomical unit is $215$ times the radius of the Sun. Sun emits radiation up to $1KWM^{-2}$. The surface gravity is $27$ times greater at the surface of the Sun than that of the Earth and it rotates at a rate of $\sim 2km.s^{-1}$. It principally contains hydrogen (90%) and helium (10%). Elements such as C, N and O together form only 0.1% of mass of the Sun [detailed composition can be found in Ander and Ebihara [1982], Breseman and Stone [1985] and Bochsler and Geiss [1999] etc.] The temperature is $\sim 15.6$ million Kelvin and the pressure is $\sim 250$ billion atmospheres.

Figure 1.1 is showing the structure of the Sun. The radiative zone surrounds the core. It acts
an insulator for the core, helping it to maintain the high temperatures needed to sustain the nuclear fusion. The convective zone surrounds the radiative zone and is the outermost layer of the interior. It is cooler and less dense than the radiative zone. This plays a large part in the creation of sunspots and flares.

The surface of the Sun is called the photosphere. It is one of the coolest layers of the sun at a temperature of $6000\, \text{K}$, and it has a density of about $10^6 \, \text{kg/m}^3$. At the photosphere, the diameter of the sun is $1.39 \times 10^6 \, \text{km}$, or about 109 times the diameter of the Earth. Large magnetic disturbances sometimes break through the photosphere and cause sunspots, which are cooler, darker regions.

The sun’s atmosphere is called the corona, the outermost layer of the solar atmosphere above the chromosphere, extends many solar radii from the sun. The corona is visible from the ground only during a total solar eclipse (or an artificial eclipse created by a coronagraph). It is composed of a very low-density gas, but extremely hot, $3 \times 10^6 \, \text{K}$, which is inferred from the emission lines of highly ionized atoms (e.g., iron atoms in the +16 charge state). The high temperature of the corona is thought to be associated with the continuous transport of energy by the magnetic field from the lower regions of the Sun to the corona. However, the details of coronal heating are yet to be fully resolved. [G.Rajaram and P.R. Pisharoty, 1998]

The space between the sun and the planets in the solar system is called interplanetary space. Here, I have only studied the interaction between the Sun and Earth; hence here interplanetary space is restricted to the space between the Sun and the Earth. This space is neither void nor quiet. This space is quite dynamic and contains plasma. Sun interact with the Earth via this space and hence it is eclectically and magnetically active.

Sun emits continuously highly conducting earthward plasma called Solar wind which is ejected radial out of the sun at an average $500\, \text{Km/s}$ in to the interplanetary space. It consists predominantly of electrons and protons with admixture of 5% Helium. The source of the solar wind is supposed to be the Sun’s hot corona. The temperature of the corona is so high that
Sun’s gravity cannot hold on to it. Solar wind expansion carry charge particles further in the interplanetary medium and densities decreases with distance from Sun, whereas temperature decreases adiabatically. At 1 AU distance, the solar wind is already dilute and become highly electrical conducting. Typical values for solar wind are provided in Table ?? given in Encyclopedia of Astronomy and astrophysics. Speed of solar wind greatly varies with the Phenomena occurring at the Sun. For example coronal holes are regions where solar plasma flows out into interplanetary space at high velocities creating regions in the solar wind known as high speed streams. These will be described in more detail in later chapters. Flares occasionally occur with Coronal Mass Ejections (CME). These are huge clouds of plasma \((10^3 \text{kg})\) that break away from the sun and expand at speeds as high as \(2000 \text{km/s}\). When CME collide with the Earth, they often excite geomagnetic storms.

<table>
<thead>
<tr>
<th>Table 1.1: Typical parameters of the Solar wind at 1 AU</th>
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<tbody>
<tr>
<td>Flow Speed (V_p) (350 \text{ kms}^{-1})</td>
</tr>
<tr>
<td>Proton density (n_p) (9 \text{ cm}^{-3})</td>
</tr>
<tr>
<td>Flux density (n_pV_p) (3 \times 10^8 \text{cm}^{-2}s^{-1})</td>
</tr>
<tr>
<td>Composition 96% protons, 4% (\text{He}^+) ions, minor constituents and electrons</td>
</tr>
<tr>
<td>Proton temperature (T_p) (4 \times 10^4 \text{K})</td>
</tr>
<tr>
<td>Electron temperature (T_p) (1.5 \times 10^5 \text{K})</td>
</tr>
<tr>
<td>Magnetic field (B) (4 \text{ nT})</td>
</tr>
</tbody>
</table>

The Interplanetary Magnetic Field \((\text{IMF})\) is an extension of the solar magnetic field that is carried frozen in to the solar wind plasma. The conductivity of the solar wind is very high and relative motion between the plasma and magnetic field is almost impossible. The interplanetary magnetic field at 1 AU is of the order of \(\sim 5 \text{nT}\), but vary within a range of \(\pm 10 \text{nT}\) or sometimes more depending upon the sun’s activity. IMF is described as IMF \(B_x\), \(B_y\) and \(B_z\), out of which last two components are particularly important for Solar-terrestrial interactions. In the solar wind the energy density of the plasma is larger than that of the magnetic field and so the plasma determines the overall motion. Since the IMF is embedded in the solar
Figure 1.2: Parker Spiral configuration of the interplanetary magnetic field (Kivelson and Russell, 1995)
wind plasma, a parcel of plasma will drag the field line radially away from the sun. The source region of the field line will be rotating with the Sun resulting to a spiral sheet of IMF known as the Parker Spiral. Figure ?? shows the spiral geometry for a constant solar wind speed of 300 km/s. The field lines carried through interplanetary space become more tightly wound as heliocentric distance increases. The angle between the field and a line drawn from the sun to an observer at 1 AU should be close to 45°, as is observed [Kivelson and Russell, 1995]. The magnetic field, motion of charge plasma together with infinite conductivity forms currents. Figure ?? is the Solar field model showing the current sheet near the equator that separates open field field lines directed outward above the sheet and inward below the sheet. Close field lines, beginning and ending in the solar corona, are also shown in the figure ?? . Solar activity and the offset of the solar magnetic pole from the spin axis create a ’ballerina skirt’ effect of the current sheet at the Earth’s distance in the Solar-ecliptic plane so that the outward- and inward-directed fields identify towards and away sectors encountering the Earth. The figure ?? is adapted from Smith, Tsurutani and Rosenberg [1978].

The Advanced Composition Explorer (ACE) satellite was launched in August of 1997 and placed into an orbit at L1 point between the Earth and the Sun. The L1 point is one of several points in space where the gravitational attraction of the Sun and Earth are equal and opposite. This particular point is located about 1.5 million km (1 million miles) from the Earth in the direction of the Sun. ACE has a number of instruments that monitor the solar wind and the spacecraft team provides real-time information on solar wind conditions at the spacecraft.

1.2 Earth’s Magnetic field and its components

It took longer time to understand the Knowledge of Earth’s magnetic field or, geomagnetism. Chinese are credited to be the earliest scholars in this field. However, it is Gilbert [1600] who came with the confirmation that Earth is a giant magnet. Later, Gauss [1838] gave the mathematical expression for magnetic field in terms of spherical harmonics. The current generated
Figure 1.3: IMF with current sheet separating the oppositely orientated magnetic field (Ballerina Skirt model)
due to convection of the molten outer core is the main source of the Earth’s Magnetic field not the earlier belief of solid iron magnet inside the Earth.

In order to model the Earth’s magnetic field behavior, spherical harmonic analysis (SHA) was used. SHA could prove that the main field of the Earth actually originates from the core of the Earth. However, Earth’s magnetic field is not exactly dipolar and hence, though not so large, significant contributions also come from the non-dipolar components.

Some basic Maxwell equations were elaborated in spherical polar co-ordinates and the solutions give rise to the separate current systems that contributes to the total magnetic field of the Earth.

\[
V = a \sum_{n=1}^{\infty} \left[ (\frac{r}{a})^n S_n^e + (\frac{a}{r})^{n+1} S_n^i \right] (1.1)
\]

Here equation (1.1) represents the potential function for the Earth’s main field derived by Gauss [1838]. Here \(a\) is the Earth’s radius and \(S\) is a function of \(\theta\) and \(\phi\). The two terms of the solution represented in above equation shows two opposite behaviors such as first term tells potential will increase while \(r\) become larges. This indicates the external source which contributes to the main magnetic field. Whereas, the second term shows that \(V\) increases with the decreasing value of \(r\). This indicates the internal contribution of total magnetic field. \(S(\theta, \phi)\) can be expressed in terms Legendre polynomials, and when equation (1.1) is expanded with the inclusion of Legendre polynomials, the equation become more simplified.

\[
V = a \sum_{n=1}^{\infty} (\frac{r}{a})^{n+1} \sum_{m=0}^{n} [g_n^m \cos(m\phi) + h_n^m \sin(m\phi)] P_n^m(\theta) (1.2)
\]

The \(g_n^m\) and \(h_n^m\) are constants called the Gauss coefficients.
Figure 1.4: Schematic diagram of the Earth’s magnetosphere showing its plasma regions
[Source:http://roma2.rm.ingv.it/en/research areas/1/earthsmagnetic field/8/elements of the geomagnetic field ]
1.2.1 Geomagnetic Field components

Main characteristic of the Earth’s magnetic field, just like as it is for all magnetic fields, is intensity $\vec{F}$ or its components. Usually Cartesian rectangular coordinates are used to resolve $\vec{F}$ into components, where x-axis is oriented towards the direction of the geographic meridian northward, -axis towards the direction of the geographic parallel eastward, z-axis is oriented downward to the center of the Earth.

Origin of co-ordinates is placed at the observation point. The projection of $\vec{F}$ onto horizontal plane is called horizontal intensity $\vec{H}$. Trimetric projection onto the x, y and z axes gives us north $X$, east $Y$ components of $H$ and vertical intensity $Z$. Vector $\vec{F}$ belongs to the plane of the magnetic meridian, the angle between the geographic and magnetic meridians is called declination $D$. Finally, the angle between the horizontal plane and the direction of vector $F$ is designated as inclination $I$. Positive D direction is to the East, positive $I$ direction is down (takes place in northern hemisphere).

\[ X = H \cos(D), Y = H \sin(D) \]  \hspace{1cm} (1.3)

\[ F = \sqrt{X^2 + Y^2 + Z^2} = \sqrt{H^2 + Z^2} \]  \hspace{1cm} (1.4)

$I$ can be defined as,

\[ \tan I = \frac{Z}{H} \]  \hspace{1cm} (1.5)

$H$ and $D$ can be represented as,

\[ H = \sqrt{X^2 + Y^2} \quad \tan D = \frac{Y}{X} \]  \hspace{1cm} (1.6)
\( \vec{F} \) is an international symbol for total field intensity vector. Declination D, inclination I, horizontal intensity, vertical intensity \( Z \), north \( X \) and east \( Y \) components are designed as the magnetic elements.

Observations show, that values of each element of the Earth magnetic field are always changing. These changes occur from hour to hour, from year to year. Such changes are called variations of the magnetic field elements. When observing these variations for a short period of time (daily) it could be seen that they are periodic, but periods, amplitudes and phases are extremely diverse. But in case of long-term elements observations (several years) with annual means determination, it is easy to estimate that annual means also change but in monotonous way, and periodicity occurs only in a very long-termed observations (about decades and hundreds of years). The slow variation of the Earth magnetic field elements is referred to as secular variation; its magnitude generally is tens of gammas a year. Secular variations of elements are driven by the changing pattern of motion in the core and is caused by the same reasons as the Earths magnetic field is.

Change in the average annual values of the particular element within a year is called secular variation. Fast periodic variation, highly variable in amplitude, have their source in electrical current of upper atmosphere.

### 1.3 Earth’s Magnetosphere

Magnetosphere is the region of surrounding space of a planet or any other astronomical objects having magnetic field in which charge particles are fully trapped and controlled by the magnetic field lines. Mostly, near surface of the planets have magnetic field of dipolar like, however, further away these can be distorted due to conducting plasma and intense electric fields. The boundary separating the magnetosphere and interplanetary space is called Magnetopause.
Figure 1.5: Earth’s Magnetosphere(Source: http://www.astro.cornell.edu/berthoud/alpsat/chapter3a.html)
The shield of magnetic lines of force of the approximate dipolar structure of the earth does not allow the highly conducting solar wind plasma to enter. The restriction made by Earth's magnetic field line gives rise to a shock and the layer called as bow shock. It forms the outermost layers of the magnetosphere. Magnetosheath is the region between bow shock and magnetopause. It is formed mainly from shocked solar wind, though it contains a small amount of plasma from the magnetosphere. It is an area exhibiting high particle energy flux, where the direction and magnitude of the magnetic field varies erratically. This is caused by the collection of solar wind gas that has effectively undergone thermalization. It acts as a cushion that transmits the pressure from the flow of the solar wind and the barrier of the magnetic field from the object.

\[
\frac{B^2}{8\pi} = 2nmv^2\cos^2(\beta)
\]

The magnetopause is the area of the magnetosphere wherein the pressure from the planetary magnetic field is balanced with the pressure from the solar wind. Equation \ref{eq:magnetopause} describe it mathematically, where \(B\) is the Earth's field strength at the magnetosphere stand-off position for the solar wind, \(n\) is the average particle density, \(m\) is the average particle mass, \(v\) is the average wind velocity and \(\beta\) is the angle between a line perpendicular to the boundary and the incident wind particles. It is the convergence of the shocked solar wind from the magnetosheath with the magnetic field of the object and plasma from the magnetosphere. Because both sides of this convergence contain magnetized plasma, the interactions between them are complex. The structure of the magnetopause depends upon the Mach number and beta of the plasma, as well as the magnetic field. The magnetopause changes size, shape and position as the pressure from the solar wind fluctuates.

Opposite to the compressed magnetic field is the magnetotail, where the magnetosphere extends far beyond the astronomical object. It contains two lobes, referred to as the northern and southern tail lobes. These two regions are of relatively smooth magnetic field, north and south of the plasma sheet. Field lines of the lobes maintain roughly the same direction until
they converge above the poles. They point towards Earth north of the equator and away from 
Earth south of it.

This region is almost empty of plasma, typical density 0.01 ion/cubic cm., the ”best vacuum” in the Earth’s vicinity. However, it contains a relatively strong magnetic field which, since it fills a large volume, can store appreciable magnetic energy. Many believe that this is the storehouse from which substorms draw their energy, releasing it quite rapidly. Further down the tail the plasma density increases, as ions from the boundary layers infiltrate the lobes.

The inner magnetosphere extends from the nose of the Magnetosphere to a distance of about 8 RE (Earth radii) on the night side, but does not include the region above the poles. This is a relatively stable region, populated by the inner and the outer radiation belt. A typical density of energetic ions is 1 per cubic cm., and the ions are matched by electrons, generally of lower energy. Typical ion energy in the outer radiation belt is 50 keV, and the electric current associated with this plasma is the ring current, encircling the Earth.

The trapped ions are gradually lost by collisions with local neutral gas or by being scattered into orbits that dip into the atmosphere. These losses are however compensated by the occasional injection of fresh plasma from the night side during magnetic storms and substorms.

The plasma sheet is a thick layer of hot plasma centered on the tail’s equator, with a typical thickness 3-7 RE, density 0.3-0.5 ions/cubic cm. and typical ion energy of 2-5 keV. Unlike the inner magnetosphere, this region is rather dynamic: thickness, density and energy vary greatly, and the plasma often flows rapidly in various directions, particularly earthward. In ”substorms” some parts of the plasma sheet may get ”squeezed out” earthwards and tailwards: earthward-flowing ions gain energy and penetrate the inner magnetosphere, while the outward moving sections (”plasmoids”) stream away from Earth and are lost. The plasma sheet, too, has its associated electric current, flowing across the tail’s equator from flank to flank, from east to west (”dawn to dusk”). It then closes along the magnetopause, and the magnetic field created by this circuit helps stretch out the tail lobes (below).
The tail lobes are two regions of relatively smooth magnetic field, north and south of the plasma sheet. Field lines of the lobes are smooth, and maintain roughly the same direction until they converge above the poles. They point towards Earth north of the equator and away from Earth south of it.

This region is almost empty of plasma—typical density 0.01 ion/cubic cm., the ”best vacuum” in the Earth’s vicinity—but it contains a relatively strong magnetic field which, since it fills a large volume, can store appreciable magnetic energy. Many believe that this is the storehouse from which substorms draw their energy, releasing it quite rapidly. Further down the tail the plasma density increases, as ions from the boundary layers infiltrate the lobes. Boundary layers are observed at times just inside the magnetopause, their thickness is generally less than 1 RE. They mark a transition between regions, and their plasma density is intermediate between that of the magnetosphere and the solar wind (e.g. 2-3 ions/cubic cm). Their ions seem to come from both of these sources, and their field lines sometimes seem to be connected to the IMF.

All the above plasma particles are fairly energetic. There exists in addition low energy plasma from the ionosphere, rotating with the Earth, and extending to about 4-6 RE with a density that gradually diminishes from up to 1,000,000 per cubic cm at an altitude of 200 km to about 10/cc at the outer limits.

Finally, a large cloud of neutral hydrogen surrounds the Earth, the ”geocorona”. Since particles in space collide so rarely, these different populations can co-exist with relatively little interference.

All these regions have been visited by satellites, and a fair amount is known about their average properties. However, their detailed structure and the way they vary with time are only poorly known, because their features (like weather) keep changing, and only a few isolated satellites are usually available to track such changes. Imagine studying the weather with only a few isolated observatories! A great deal of ingenuity has been applied in the past to exploring the Earth’s magnetosphere, but the greatest need now is to go for many more simultaneous
and coordinated observations in the various regions of earthspace.

1.3.1 Motion of charge particles in side the Magnetosphere

Here, different types of motions that a trapped charged particle performs inside the magnetosphere is discussed in brief. In order to describe all types of motions, one has to go through single particle approach where it is assumed that charged particles do not directly interact with each other and where they do not affect the magnetic field significantly. In general three types of motions can be seen viz. Gyro motion, Bounce motion and Drift motions. Figure ?? illustrates these motions.

Gyro motion can be explained as the motion controlled by the Lorentz force in the presence of magnetic field.

Then, the equation of motion will be,

\[ m \frac{d\vec{v}}{dt} = q(\vec{v} \times \vec{B}) \]  

where, \( m \) is the mass of the charge particle, \( q \) is the charge of the particle. \( \vec{v} \) and \( \vec{B} \) are the velocity of the particle and magnetic field respectively.

Hence, the angular frequency of the charge particle will be,

\[ \omega_g = \frac{qB}{m} \]  

where \( w_g \) is the angular frequency of the charge particle.

The helical path of a charged particle while gyrating in Earth’s dipolar magnetic field gets influenced by the increasing flux density of field lines towards poles. Invariance of the magnetic dipole moment leads to increase in the charged particles perpendicular kinetic energy.
At a point where, the total energy of the charged particle equate to its perpendicular kinetic energy i.e when parallel velocity \(v_{\parallel}\) is zero, particle reverses its direction and bounce back. The point is called mirror point.

Addition to these motion, charged particles perform different types of drift motion depending upon the type of force acting on it. Basically, drift motion is the shifting of the guiding centre. with the drift velocity \(\vec{V}_d = \frac{E \times \vec{B}}{B^2}\), different types of drifts are mentioned below,

- **\(E \times B\) drift** can be explained as
  \[
  V_E = \frac{E \times B}{B^2}
  \]  
  \[\text{(1.10)}\]

- **Polarization drift** can stated as
  \[
  V_P = \frac{1}{\omega_g B} \frac{dE_\perp}{dt}
  \]  
  \[\text{(1.11)}\]

- **Gradient and curvature drift** together explain the total magnetic drift and can be written as,
  \[
  V_B = V_R + V_\Delta = (V_\parallel^2 + V_\perp^2) \frac{B \times \Delta B}{\omega_g B^2}
  \]  
  \[\text{(1.12)}\]

### 1.3.2 Current system in Magnetosphere

Figure ?? illustrates the schematic view of magnetospheric currents. The compressed day side magnetosphere is associated with a current that flows normal to the magnetic field lines at the surface of the magnetopause called *magnetopause current* or *Chapman-Ferraro current*. It is caused by the deflection of the electrons and ions in the magnetopause in opposite direction normal to the field. The different gyro radii of electrons and ions also cause a charge separation and an electric field.
The tail like structure at the back of the Earth extends anti-sunward and is also accompanied with *tail-current* which flows at the surface of the tail. *Neutral sheet current* is associated with the central plasma sheet and flows across the magnetosphere from dawn to dusk. *Ring current* is one among the large scale current of the magnetosphere current system. It also largely affects the inner magnetosphere and man made observational facilities in space with the advent of the satellite era. Hence, it is extensively studied by the scientific community. Ring current flows westward at radial distance of 2-8 Re. This current exist by the trapped protons that drifts westward and trapped low energetic electrons ($\sim K eV$)those drift eastward across the magnetic field lines due to gradient curvature drift.

At high latitude, *auroral current* predominantly exits. These currents flow at altitudes of 100-150 km, E-region of ionosphere. These auroral electrojets are very much confined to
Figure 1.7: Current system inside the magnetosphere [After C.T. Russell]
auroral oval, a latitudinal range of $65 - 70^\circ$ CGM. However, these currents can expand poleward as well as equatorward depending up on the level of perturbation in the magnetosphere during intense geomagnetic activity. Precisely, these currents are related to substorm activities which are explained in the subsection 1.5.2. Similar to the altitude of auroral current, solar quiet current or, Sq- current also flows in the same altitude but occur at day-side mid-latitude ionosphere and the equatorial electrojet over the magnetic equator. Sq-current is essentially caused by solar illumination of the ionosphere and it is completely restricted to day side of the magnetosphere.

All the above currents flow perpendicular to the magnetic field. *Field align currents* or *Birkland currents* flow along geomagnetic field lines connecting the Earth's magnetosphere to the Earth's high latitude ionosphere. These currents are driven by the solar wind and interplanetary magnetic field and by bulk motions of plasma through the magnetosphere (convection indirectly driven by the interplanetary environment). The strength of the Birkeland currents changes with activity in the magnetosphere (e.g. during substorms). Small scale variations in the upward current sheets (downward flowing electrons) accelerate magnetospheric electrons.

### 1.3.3 Particle precipitation processes

The principles of how and why particles precipitate into the atmosphere is a wide and still highly debated topic that is beyond the scope of this work. Generally speaking for a particle to precipitate its pitch angle must change enough to place the particle within the loss cone such that on the next bounce, the particle will not mirror but instead will be lost to the atmosphere. For the pitch angle to change the ratio of the parallel and perpendicular velocities of the particle must alter since a generally accepted mechanism for altering pitch angles is through the doppler shifted cyclotron resonance with very low frequency (VLF) waves. A gyrating electron may feed energy into a VLF wave by transverse resonance so reducing its velocity perpendicular to the magnetic field line; the electron and wave must be anti-parallel. A spectrum of VLF signatures alters the pitch angle distribution of trapped particles causing
some to be lost at the next bounce. A non-isotropic pitch angle distribution is unstable; the particles produce waves which then alter the pitch angles such that the distribution becomes more isotropic. The point of interaction is usually taken to be in the equatorial region. Similarly to the electron-whistler interaction, ion cyclotron waves (ULF) couple to gyrating ions and lead to precipitation. A number of authors have dealt with the loss of charged particles to the atmosphere due to pitch angle diffusion driven by VLF/ULF waves (e.g. Brice, 1964; Kennel and Petschek, 1966; Cornwall, 1966; Kennel, 1969).

1.4 Ionosphere

The ionosphere is a region of Earth’s upper atmosphere that is weakly ionized and thus conduct electricity, ranging from about 60 km to 1,000 km altitude. It is located approximately in the same region as the top half of the mesosphere and the entire thermosphere and some part of exosphere. It is ionized by solar radiation, plays an important part in atmospheric electricity and forms the inner edge of the magnetosphere. It affects the radio wave propagation.

In the ionosphere, the molecules and atoms in the air are ionized mostly by the Sun’s ultraviolet, x-ray, and corpuscular radiation, and partially by cosmic rays, resulting in ions and free electrons. The ionization process depends on many factors such as the Sun’s activity (e.g., sunspot cycles), time (e.g., seasonal or daily changes), or geographical location (different at polar regions, mid-latitudes or equatorial zones).

Figure ?? is showing the structure of the neutral atmosphere and the Ionosphere. The ionosphere can be further divided into sub-regions according to their free electron density profile that indicates the degree of ionization, and these sub-regions are called the D, E, and F layers. The D layer is located lowest among them, and it does not have an exact starting point. It absorbs high-frequency radio waves, and exists mainly during the day. It weakens, then gradually even disappears at night, allowing radio waves to penetrate into a higher level of the
ionosphere, where these waves are reflected back to Earth, then bounce again back into the
ionosphere. This explains why AM radio signals from distant stations can easily be picked up
at night, even from hundreds of miles. Above the D layer, the E layer (or Kennelly-Heaviside
layer) can be found, which historically was the first one that was discovered. After sunset, it
usually starts to weaken and by night, it also disappears. The E layer absorbs x rays, and it
has its peak at about 65 mi (105 km). The F layer (or Appleton layer) can be found above
the E layer, above 93 mi (150 km), and it has the highest concentration of charged particles.
Although its structure changes during the day, the F layer is a relatively constant layer, where
extreme ultra-violet radiation is absorbed. It has two parts: the lower F1 layer, and the higher
and more electron-dense F2 layer.

The free electrons in the ionosphere allow good propagation of electromagnetic waves, and
excellent radio communication. The ionosphere is also the home for the aurora, a light dis-
play mostly in the night sky of the polar areas, caused by excited and light-emitting particles
entering the upper atmosphere.

1.4.1 High latitude ionosphere

High latitude ionosphere is much more complex than equatorial or low latitude ionosphere.
The first and foremost things that differ high latitude ionosphere from the rest is the process
of ionization. It is mostly ionized by low energetic protons at the polar cap regions because
of the direct access of solar winds, where there is no shielding of magnetic lines of forces and
ergetic particle precipitations from the magnetospheric plasma sheet at high latitude, usually
at the auroral oval.

Since field lines open to the IMF thread the polar cap, direct entry of solar wind particles is
possible This produces a drizzle of low energy particles termed the polar rain. Conversely
light ions of ionospheric origin (mostly H+ and He+) are also lost from the high altitude
polar cap. The energies of these ions is sufficient to escape the gravitational potential well
and so they travel along the open flux tubes in the polar cap. This is referred to as the polar wind. Little down to polar cap region, High-energy particles (\(\lesssim\) keV) can precipitate along the magnetic field lines from the plasma sheet regions. However, there are various mechanisms for describing how these particles are accelerated to these high energies and are not yet fully understood. But once they enter into the atmosphere, they excite neutral species which subsequently result in to ionization, emitting photons and producing the optical aurora. Excitation of the different atmospheric species such as atomic oxygen, molecular nitrogen and related radiations produce aurora of different colors. This auroral precipitation is confined to a zone (the auroral oval) centred on the magnetic pole. The boundary of the oval extends to lower latitudes on the nightside than on the dayside. Optical aurora broadly fits into two
Figure 1.9: High latitude current boundaries
categories, diffuse and discrete. The discrete aurora is structured and intense whereas the
diffuse aurora appears as a glow in the sky. Both have similar overall intensities but the dis-
crete form is easier to observe due to the low intensity per unit area of the diffuse form. The
discrete aurora maps to the plasma sheet boundary layer and appears poleward of the diffuse
aurora, which is linked to the central plasma sheet. Particle precipitation plays an important
role in the coupling between the ionosphere and the magnetosphere. Associated with the au-
rrora is auroral radio absorption. This is produced by the more energetic particles (usually
electrons) that penetrate to the lower layers of the ionosphere. The precipitation of these en-
ergetic particles enhances the electron density allowing the formation of a D layer at night
when photo-ionisation has ceased. The enhanced electron concentration leads to absorption
of high frequency radio waves in the ionosphere. This band of precipitation tends to maximise
equatorward of the auroral oval and is more circular in nature. It is mostly associated with the
diffuse aurora but often occurs collocated or close to auroral arcs.

1.4.2 Radio wave absorption in ionosphere

The central theme of this thesis is mainly based on imaging Riometer instrument, which is
nothing but set of passive radio recievers arranged in buttler matrix form. Mainly, it records
the cosmic noise signal which is in radio wave frequency which may vary day to day depend-
ing upon the ionospheric state. The enhanced ionization in the D-region inosphere at high
latitude majorly controlled by the precipitation of charge particles.Hence, it affect the radio
waves. An increase in ionospheric density will lead to changes in the refractive index causing
the deviation of waves from their original paths. It can also lead to significant drops in signal
strength due to attenuation in the lower ionosphere. As radio waves propagate through mat-
ter, they will interact with the matter. The basic interactions are [Hunsucker and Hargreaves,
2003]

- Reflection
Attenuation process is the product of partial radio wave absorption in the ionized medium. For accounting the process of absorption while an electro-magnetic wave passes through a plasma medium, the wave number $k$ should be complex. The refractive index $\eta$ can be described in terms of complex number as

$$\eta = (\mu - i\chi) = \frac{k c}{\omega}$$  \hspace{1cm} (1.13)

where $\mu$ is the real part of the complex refractive index, $\chi$ is the imaginary part and $\omega$ is the angular frequency.

The Appleton-Hartee equation [Davis, 1966] have explained the refractive index in terms of the plasma properties,

$$\eta^2 = (\mu - i\chi)^2 \quad = 1 - \frac{X}{1 - iZ - \frac{Y^2 \sin^2 \theta}{2(1-X-iZ)} - \left[ \frac{Y^4 \sin^4 \theta}{4(1-X-iZ)^2} + Y^2 \cos^2 \theta \right]^{1/2}}$$  \hspace{1cm} (1.14)

where,

$$X = \frac{\omega_p^2}{\omega^2} = \frac{N_e e^2}{\epsilon_0 m_e \omega^2}$$

$$Y = \frac{\omega_H}{\omega} = \frac{e B}{m_e \omega}$$

$$Z = \frac{\nu_m}{\omega}$$

$\omega_H$ is the angular electron gyrofrequency, $\omega_p$ is the plasma angular frequency, $N_e$ is the electron number density, $e$ is the electron charge, $B$ is the background magnetic flux density, $\nu_m$
CHAPTER 1. Introduction

is the electron momentum-transfer collision frequency, $\theta$ is the angle between the magnetic field and the wave vector $k$, and $\epsilon_0$ is the permittivity of free space.

While an electromagnetic wave passes through plasma medium, it faces two types of absorption such as Deviative and non-deviative. Deviative absorption occur at F-region where the collision frequency is less with high electron density. In this case, dispersion relation becomes

$$\eta^2 = \mu^2 = 1 - X$$ \hspace{1cm} (1.15)

which leads to

$$k = \nu \left( \frac{1}{\mu} - \mu \right)$$ \hspace{1cm} (1.16)

Non-deviative absorption take place when the medium has high collision frequency. The electromagnetic wave accelerate plasma which further leads to enhancement in collision and this way wave losses its energy to thermal energy of the plasma. The cosmic noise absorption is mostly of the non-deviative type. To calculate the proportion of wave power lost to this non-deviative absorption in a simplified way, as assumption is made that the radio wave propagation will be close to the direction of the magnetic field which is broadly agree the situation at high latitude. Hence $\sin \theta \to 0$. Then the equation ?? will reduce to

$$(\mu - i\chi)^2 = 1 - \frac{\omega_p^2/\omega^2}{1 - \frac{\nu_m}{\omega} \pm \frac{\omega H \cos \theta}{\omega}}$$ \hspace{1cm} (1.17)

The imaginary part of the complex wave number, commonly given the symbol $k$, represents an evanescent component of the wave.

By separating ?? in to its real and imaginary parts, the Appleton-Hartree equation for the absorption coefficient, $k$, of mono-energetic electrons (i.e. electrons sharing the same collision frequency) is found

$$k = \frac{e^2}{2m_e c \epsilon_0} \frac{1}{\mu} \frac{N_e \nu_m}{\nu_m^2 + (\omega \pm \omega_H \cos \theta)^2 N \nu_p/m},$$ \hspace{1cm} (1.18)
where $\nu_m$ is the energy-dependent electron-neutral momentum-transfer collision frequency. The $\pm$ applies to absorption of left-hand and right-hand circular wave polarizations respectively, which are conventionally referred to as the O and X modes. Therefore, cosmic noise absorption is a function of electron-neutral momentum transfer collision frequency, and electron density. Where, the electron-neutral momentum transfer collision frequency is integrated over the electron energy distribution and the electron density is integrated over the path length of the incoming radio signal.

The final form of the equation after some trivial algebra as described in Davis [1989] is given as

$$\text{Absorption} = 4.6 \times 10^{-5} \int \frac{N_e \nu_{eff}}{\nu_{eff} + (\omega \pm \omega_H \cos \theta)^2} dl$$

(1.19)

1.5 Solar wind Magnetosphere- Ionosphere system

As per John G. Lyon’s review article [2000] in Science states that the solar wind, magnetosphere and Ionosphere form a single system driven by transfer of energy and momentum from the Solar wind to the magnetosphere and finally reach to Ionosphere. The coupling between the solar wind and magnetosphere is primarily controlled by magnetic reconnection process which is highly debatable topic. However, this results in various types of geomagnetic disturbances as discussed below.

1.5.1 Geomagnetic storms

Sometimes, more particles than usual are injected from the tail in to the ring current region. This gives rise to increase in the total energy of the ring current and cause additional
depression in the magnetic field in near-equatorial magnetometers. This event is called a ge-omagnetic storm. While measuring the depression in the magnetic field at near equatorial stations, it is convenient to look for disturbance storm time or, DST index (details of the index is describes in 'Indices' section). Figure?? has shown a historical geomagnetic storm that occurred in 12-16 July,1982, mentioned in Gonzalez et. al. 1994. The minimum DST value has dipped less than -300 nT. During a geomagnetic storm, increase in the convection electric field is seen to be strong for an extended period of time.

Basically, a geomagnetic storm has three phases: initial, main and recovery. The initial phase is characterized by Dst (or its one-minute component SYM-H) increasing by 20 to 50 nT in tens of minutes. The initial phase is also referred to as a storm sudden commencement (SSC). An increased solar wind pressure pushes the magnetopause inwards leading to a growth in the magnetopause current. However, not all geomagnetic storms have an initial phase and not all sudden increases in Dst or SYM-H are followed by a geomagnetic storm. The main phase of a geomagnetic storm is defined by Dst decreasing to less than -50 nT. During the main phase of the storm, the IMF turns southward. This increases the convection electric field and results in more particles being transported from the geomagnetic tail and closer to the Earth. During their inward convection, the particles are accelerated. These particles contribute to the ring current resulting in a decrease of the Dst-index. This phase can last from hours to days, depending on the intensity of the storm. The selection of -50 nT to define a storm is somewhat arbitrary. The minimum value during a storm will be between -50 and approximately -600 nT. The duration of the main phase is typically 28 hours. The recovery phase is when Dst changes from its minimum value to its quiet time value. During the recovery phase, the IMF will turn north and thus reducing the sunward convective flow of particles. The recovery phase may last as short as 8 hours or as long as 7 days.

The size of a geomagnetic storm is classified as moderate (-100 nT < minimum of Dst < -50 nT), intense (-250 nT < minimum Dst < -100 nT) or super-storm (minimum of Dst < -250 nT)
1.5.2 Magnetospheric substorm

Magnetospheric substorm is related to the processes that occur throughout the magnetosphere at the time of an auroral and magnetic disturbance. The term substorm is used to signify that the processes produce an event, more localized to high latitude, which is distinct from a magnetic storm. During a substorm, the aurora near midnight exhibits a sequence of changes called the auroral substorm. Accompanying the changes in the aurora is a sequence of magnetic variations referred to as the polar magnetic substorm. Most of the detrimental effects of a magnetic storm are caused by the substorms that accompany them.

A substorm begins when the IMF turns southward and dayside reconnection begins. For about an hour afterward, bands of quiet auroral arcs drift equatorward near midnight in the northern
and southern auroral ovals. The eastward and westward electrojets, flowing from noon toward midnight along the ovals, gradually increase in strength and move equatorward along with the aurora. This quiescent phase is called the growth phase of the substorm.

The growth phase is terminated by a sudden brightening and activation of the most equatorward arc in each oval. This event is often termed the auroral breakup, and it signals the onset of the substorm expansion phase. Detailed observations made from the ground and images from satellites reveal that the region of auroral disturbance expands poleward and westward. A surge of bright aurora, known as the westward traveling surge, propagates to the west and eventually decays into drifting bands that sometimes pass the dusk meridian. On the dawn side, patches of pulsating aurora and large omega-shaped bands drift eastward. The final phase of a substorm is called the recovery phase. During this phase the aurora and currents gradually drift back to their original equatorward locations as they simultaneously decrease in luminosity and strength.

The magnetospheric substorm also can be explained in terms of magnetic convection driven by magnetic reconnection. A substorm, however, is a manifestation of time-varying convection. In the reconnection model of substorms, transport of magnetic flux and particles never reaches equilibrium. During the growth phase of a substorm, magnetic flux is eroded from the dayside and added to the lobes of the magnetotail. The dayside magnetopause moves inward as a result of the flux lost, while the polar caps increase in size as a result of the flux gained. The additional flux in the near-tail requires an increase in the tail field and hence in the tail current, since the additional flux is contained in a volume of smaller cross section than was the initial quiet-time flux. Also, because the tangential drag on the tail has increased, the tail current moves earthward to increase the force that the Earth exerts on the tail, thus balancing the additional force of the solar wind. Closed flux simultaneously begins returning to the dayside and emptying the nightside plasma sheet. Equatorward motion of the aurora during this phase is simply a manifestation of the increasing size of the tail lobes. Enhancements of
the eastward and westward electrojets are a consequence of the increased rate of convection driven by the southward IMF.

The expansion phase is less well understood than the growth phase. Many investigators support the near-Earth neutral-line model, but concurrently other explanations have been suggested. In the neutral-line model a localized x-type neutral line is formed inside the plasma sheet somewhere between 20 and 40 Re (Earth radii) behind the Earth. The left part of the figure shows the topology of the magnetic field when such a line is first formed. In the noon-midnight meridian of the magnetotail the magnetic field is divided into several regions by the simultaneous presence of two x-type neutral lines. Between the two x lines is an o-type neutral line around which there are closed loops of magnetic field. This field connects to neither the solar wind nor the Earth and remains in place only because it is surrounded by a sheath of field lines attached to the Earth. This geometry persists only as long as the sheath remains. Eventually reconnection severs the last-closed field lines, and subsequently open field lines of the tail lobe begin to reconnect. Shortly after this happens, the region of closed field lines is sheathed by field lines connected to the solar wind. Tension in these field lines pulls the bubble of plasma and field, or plasmoid, from the centre of the magnetotail. The plasmoid travels down the tail, collapsing the plasma sheet behind it.

In the neutral-line model the sudden brightening of the auroral arc near midnight is thought to occur when reconnection reaches the last-closed field lines. The subsequent poleward expansion of the aurora is interpreted as the boundary of lobe field lines moving into the near-Earth neutral line to be reconnected. Finally, the westward surge is explained as an expansion of the azimuthal extent of the near-Earth neutral line by some as-yet-unexplained process.

In this model the final recovery stage of an isolated substorm is produced by a rapid tailward motion of the near-Earth neutral line. This probably occurs when there is no longer excess magnetic flux in the tail lobes to be returned to the dayside. Once this happens, the magnetic field and plasma flow in the near-Earth region of the tail return to quiet-time conditions and
reestablish the presubstorm conditions of aurora and magnetic disturbance. An essential feature of this model is that the near-Earth neutral line is azimuthally localized. To achieve this localization, it is necessary to divert a portion of the tail current to the ionosphere at the ends of the neutral line. The sense of this diversion is downward toward dawn and upward toward dusk, as shown schematically in the figure. In the ionosphere the current flows westward and enhances the preexisting westward convection electrojet. This current system is called the substorm wedge and connects symmetrically to both northern and southern auroral ovals.

Figure 1.11: The substorm cartoon is from W. Baumjohan and R.A. Treumann, Basic Space Plasma Physics, 1996
However, there is one more notable model is current sheet disruption (CSD) model. It basically describes the instability in the near-Earth (6-10 Re) current sheet may responsible for substorm expansion phase onset. Disruption of the near-Earth current sheet triggers either the formation of a new reconnection region in the mid-tail, or a rapid increase in the reconnection rate at a previously formed reconnection region (Lui, 1991). The NENL model, on the other hand, identifies the formation of a new near-Earth reconnection region at about 20 Re as the unique initiator of the expansion phase, and views the disruption of the near-Earth current sheet to be a consequence of reconnection in every case (Baker et al., 1996). The mechanism for CSD is assumed to be a kinetic instability in the near-Earth tail. At the end of the growth phase it is known that the north-south scale size of the current sheet is on the order of, or smaller than, an ion gyroradius (Lopez et al., 1989; Sergeev et al. 1993). This led Lui et al. (1990) to suggest that a kinetic cross-field streaming instability was the agent.

Substorms is also linked with the sudden and temporal geomagnetic variations observed at ground as well as in space. The temporal period of such variations fall in the category of geomagnetic pulsations (mentioned in the next subsection). The irregular and impulsive pulsation comes in range of 40 to 150 s are defined as Pi2 pulsations. Pi2 are considered as the manifestation of the onset of field-aligned currents and compressional waves in the near-Earth plasma sheet associated with substorm onset [Olson, 1999].

1.5.3 Geomagnetic pulsations

Ultra low frequency waves (period 1-1000s) observed on the Earth, are a common occurrence during all forms of magnetic activity. Geomagnetic pulsations were first observed in the ground-based measurements of the 1859 great aurora events (Stewart, 1861). The processes in the magnetosphere and solar wind produce a wide variety of ULF waves that are classified on the basis of waveform (c=continuous, i=irregular) and time period [Jacobs et al., 1964;Obayashi and Jacobs, 1957]. These are basically the hydromagnetic oscillations also known as Alfven waves first suggested by Alfven[1942]. According to Alfven, these waves
propagate along the field lines with a velocity whose square is equal to the magnetic stress density divided by the ionic density \( \rho_i \),

\[
V = \frac{H}{\sqrt{4\pi \rho_i}}
\] (1.20)

<table>
<thead>
<tr>
<th>Types of Pulsations</th>
<th>Pc1</th>
<th>Pc2</th>
<th>Pc3</th>
<th>Pc4</th>
<th>Pc5</th>
<th>Pi1</th>
<th>Pi2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>0.2-5s</td>
<td>5-10s</td>
<td>10-45s</td>
<td>45-150s</td>
<td>150-600s</td>
<td>1-40s</td>
<td>40-150s</td>
</tr>
<tr>
<td>Freq.</td>
<td>0.2-5Hz</td>
<td>0.1-0.2Hz</td>
<td>22-100mHz</td>
<td>7-22mHz</td>
<td>2-7mHz</td>
<td>0.025-1Hz</td>
<td>2-25mHz</td>
</tr>
</tbody>
</table>

Figure 1.12: Geomagnetic pulsations

### 1.6 Indices

In order to characterize, to measure and to identity these various types of space weather activity, many researcher such as Bartels et al., 1939; Davis and Sugiura, 1966; Iyemori and Rao, 1996; Rangarajan, 1989; Sugiura, 1964, etc have formulate various kind of indices. These indices are so far used to measure the solar terrestrial interaction. However, requirement of deep understanding of these phenomena require to more sophisticated tools such as balloons, rockets and satellites. Use of these indices in conjunction with in-situ measurements are still considered to be a great idea. Some indices represent the overall state of the magnetosphere, whereas some define the conditions of the localized area of the magnetosphere. Some of these indices are used extensively in this study and hence have been discussed below:
1.6.1 **Auroral Indices** $(AU, AL, AO$ and $AE)$

The hourly and minutes Auroral Electrojet $(AE)$ index shows the aurora related geomagnetic activity around the auroral oval of the northern hemisphere. It was firstly introduced by Davis and Suguira [1966]. The AE index is derived from geomagnetic variations in the horizontal component observed at selected (10-13) observatories along the auroral zone in the northern hemisphere. To normalize the data a base value for each station is first calculated for each month by averaging all the data from the station on the five international quietest days. This base value is subtracted from each value of one-minute data obtained at the station during that month. Then among the data from all the stations at each given time (UT), the largest and smallest values are selected. The $AU$ and $AL$ indices are respectively defined by the largest and the smallest values so selected. The symbols, $AU$ and $AL$, derive from the fact that these values form the upper and lower envelopes of the superposed plots of all the data from these stations as functions of UT. The difference, $AU$ minus $AL$, defines the $AE$ index, and the mean value of the $AU$ and $AL$, i.e. $(AU + AL)/2$, defines the $AO$ index. The term "AE indices" is usually used to represent these four indices ($AU$, $AL$, $AE$ and $AO$). The $AU$ and $AL$ indices are intended to express the strongest current intensity of the eastward and westward auroral electrojets, respectively. The $AE$ index represents the overall activity of the electrojets, and the $AO$ index provides a measure of the equivalent zonal current. The $AE$ index is now widely used for researches in geomagnetism, aeronomy, and solar-terrestrial physics. One can get these data form World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/).

1.6.2 **$Dst$, $SYM – H/D$ and $ASY – H/D$**

As mentioned in the section 1.5.1, a geomagnetic storm has three phases. The first phase or the initial phase consist of SSC with typical positive value in the horizontal component ($H$-component) at mid latitude and near equatorial stations magnetometer. Then a large global
CHAPTER 1. Introduction

decrease in H begins, indicating the development of the main phase of the storm. The magnitude of the decrease in H represents the severity of disturbance. In order to measure such disturbances, disturbances storm time (Dst) index is used. For the derivation of the Dst index presented in this report, four magnetic observatories, Hermanus, Kakioka, Honolulu, and San Juan are used. Dst index is an hourly index and is an indicator of ring current enhancement. Higher depression in the Dst index confirms the stronger ring current presence. In order to get high resolution of the ring current status, longitudinally asymmetric (ASY) and a symmetric (SYM) disturbance index are introduced [Iyemori, 1990, 1996] and derived for both H and D components, that is, for the components in the horizontal (dipole pole) direction H (SYM − H, ASY − H) and in the orthogonal (East-West) direction D (SYM − D, ASY − D). The symmetric disturbance field in H, SYM − H, is essentially the same as Sugiura’s hourly Dst index (Sugiura and Poros, 1971) except that it has one minute resolution compared to Dst of hourly resolution. The ASY − H asymmetric disturbance component in H is close to the asymmetric indices proposed by Kawasaki and Akasofu (1971), Crooker and Siscoe (1971) or Clauer et al.(1983). It is seen that ASY − H is correlates well with the AE index.

1.6.3 Wp-index

Identifying the substorm onset is one of the challenging task in the study of high latitude geomagnetism. There are several ground signatures for substorm onset such as traditional AE index, Pi2 pulsation and positive bay at the night side low latitude. In 2008, Nose introduced a new index called Wp-index. This index is related to wave power of low-latitude Pi2 pulsations. In derivation of the Wp index, wavelet analysis is adopted. Geomagnetic field data used for the index are the H and D components from geomagnetic latitude range of 21° – 48°.
1.6.4 $K$, $K_p$, and $ap$

The $K$-index is quasi-logarithmic local index of the 3-hourly range in magnetic activity relative to an assumed quiet-day curve for a single geomagnetic observatory site. First introduced by J. Bartels in 1938, it consists of a single-digit 0 thru 9 for each 3-hour interval of the universal time day (UT).

The planetary 3-hour-range index $K_p$ is the mean standardized $K$-index from 13 geomagnetic observatories between 44 degrees and 60 degrees northern or southern geomagnetic latitude. The scale is 0 to 9 expressed in thirds of a unit, e.g. 5- is 4 2/3, 5 is 5 and 5+ is 5 1/3.

1.7 Scope of the thesis

Particle precipitation at high latitude in the various energy band (e.g. 10 KeVs to 10s of MeV) and corresponding changes in the electrodynamics of the Ionosphere has always been the major concerned in solar terrestrial science. There are various types of processes that contributes to precipitation of charge particles either electrons or protons or both at high latitude. High latitude atmosphere has direct access to the magnetospheric charged particle either by open field lines or closed field lines depending upon their relative position to the geomagnetic poles, for example polar cap has direct access to the incoming plasma from the sun, where as auroral latitude get affected by the closed field line precipitation by the formation of substorm current weidge. Additionally, the electrons associated with central plasma sheet, being injected in the night side of the magnetotail, mostly in midnight hours and further fall into loss cone during gradient-curvature drift in the inner magnetosphere and subsequently precipitate in to the auroral atmosphere. All these processes not only make high latitude ionosphere complex but also make the study of high latitude ionosphere much more interesting and important. Adding things to the importance of high latitude ionosphere and related space weather processes, now-a-days, impact of these space weather activity on the climate change
CHAPTER 1. Introduction

is getting attention from the scientific community. Many workers [Sheila et al, 2015] already confirmed that enhanced Precipitating particles during high speed solar wind (HSS) events affect the neutral chemistry of the polar middle atmosphere. In last few decades, it has been shown that production of NOx in the mesosphere region during the precipitation of charged particles (with energy range >30 KeV to 1 MeV) [Meredith et al., 2011] is directly related to the ozone loss in the polar middle atmosphere, extending from mesosphere to upper stratosphere [Rodger et al., 2007].

A decade has already elapsed for the geomagnetic study at the second permanent Indian Antarctic research station, Maitri. The geomagnetic study at that location (L= 5; CGM 62.45° S, 55.45° E), which is a sub-auroral location is strategically important for Auroral substorm dynamics and related particle precipitation study. However, presence of a single digital fluxgate Magnetometer (DFM) and a wide beam riometer could not serve this purpose. India had its first imaging Riometer installed at the Indian Antarctic station, Maitri during Austral summer of 2009-2010. Hence, this thesis is dedicated to explore the dynamics of auroral currents and concurrent particle precipitations over Maitri during geomagnetic disturbances i.e. magnetospheric substorm and geomagnetic storm events using imaging Riometer predominantly along with other measurements such as Ground Magnetometer, satellite observations for interplanetary parameter, Satellite particle flux data, X-ray data and GPS TEC data. Therefore, this thesis is an initiative to a process of deep understanding the auroral activity and related particle precipitation at a sub-auroral location, Maitri.

Chapter 2

Here, the new imaging Riometer experimental set up at Maitri (L= 5; CGM 62.45° S, 55.45° E), Antarctica has been explained. Interestingly, Ionospheric study using Riometer has been initially proposed by Indian scientists. A brief section is dedicated to Indian perspective of ionospheric study using this technique. This chapter has also pointed out the importance of location for installation of this instrument and related observations in view of space weather activities. Significance of imaging Riometer over a simple Riometer and essential features of
the instrument are described here in details. Finally, some initial results by using imaging Riometer data in corroboration with ground magnetic and satellites observations have been documented.

Chapter 3

This chapter precisely dealt with the substorm related particle precipitations and subsequent cosmic noise absorption at Maitri, Antarctica. A comprehensive study has been carried out for the substorm related CNA events where simultaneous westward auroral electrojet current enhancement and CNA production are evident during the substorm process. The level of CNA and expansion of CNA is seen to be dependent upon the level of substorm activities. For this study one year data of imaging Riometer from Maitri has been analyzed along with other data sets e.g. magnetometer data for auroral electrojet signature and ACE satellite data for interplanetary parameter study. The local time distribution of these events are also discussed. This chapter also shows the role of interplanetary parameters during the occurrences of substorm related CNA events.
Chapter 4

This chapter deals with the day side CNA event. Unlike the substorm related CNA events those discussed in the previous chapter, these kind of CNA are owing to different type of magnetospheric phenomena which involves wave-particle interactions. Again, this work has focused Maitri as the prime location of study. However, a set of different riometer stations were taken to validate the observations. The comparative study has been carried out in the light of ground magnetic signatures, Riometer signatures, interplanetary conditions, GOES satellites observation of particle fluxes in different energy bands (40, 75, 150, 275 and 475 KeV) and associated pulsations. Additionally, successive delays of the onset of CNA at longitudinally distributed stations inside the auroral oval have also been examined. Temporal delay between the onset of the substorm and onset of CNA at Maitri has been attributed to the azimuthally gradient drift of energetic electrons. We use this delay time in the gradient-curvature drift equation (Baharell et.al, 2015) to get an order of energy estimate of the electron fluxes. The abrupt enhancements in electron fluxes in certain energy bands as observed from different GOES satellites could result into the occurrences of day side CNA event as observed on 02 April, 2011.

Chapter 5

The largest geomagnetic storm of the current solar cycle (solar cycle 24) has recently occurred in the St. Patrick’s day. Some published scientific articles named it 2015, St. Patrick’s geomagnetic storm. This study has dealt with the CNA (cosmic noise absorption) event as observed at Maitri, Antarctica (L = 5; CGM 62.45° S, 55.45° E) during the first day of the recovery phase of the 2015, St. Patrick’s geomagnetic storm. Though the production of CNA is pronounced during the main phase of the storm, the CNA enhancement during the first day of recovery phase, particularly 14-17 MLT at Maitri is of the major concerned in this study. The CNA pattern exhibits oscillation in the Pc5 range and is in simultaneity with geomagnetic pulsations during the same hours. It is found that the intense CNA production is mainly due to hiss-driven sub-relativistic electrons. Absence of EMIC (Electro-magnetic Ion-cyclotron)
CHAPTER 1. Introduction

waves is marked which confirm the role of VLF waves in causing precipitation. Additionally, signature of enhanced eastward electrojet at Maitri during 14-17 MLT at Maitri could be an additional factor for such large CNA. Further, the spatial characteristics of Pc5 waves during the CNA event were critically examined using IMAGE chain magnetometers.

Chapter 6

The final chapter comprises of the summary of work done during the course of the thesis. It also presents scope for the future work.
Chapter 2

New imaging Riometer at Maitri, Antarctica

2.1 Introduction

This chapter has introduced the new imaging Riometer experimental set up at Maitri (L=5; CGM 62.45°S, 55.45°E), Antarctica. Interestingly, Ionospheric study using Riometer has been initially proposed by Indian scientists. A brief section is dedicated to Indian prospective of ionospheric study using this technique. This chapter has also pointed out the importance of location for installation of this instrument and related observations in view of space weather activities. Significance of imaging Riometer over a simple Riometer and essential features of the instrument are described here in details. Finally, some initials results by using imaging Riometer data in corroboration with ground magnetic and satellites observations have been documented.

Maitri is the second Indian permanent research station built in 1989 at east Antarctica dedicated for various scientific studies. Precisely, it is located at rocky mountainous region called
Schirmacher Oasis. Russian station Novolazarevskaya is only 05 km east to Maitri. Recently, India has built its third fully sophisticated and modernized state of the art station called Bharati at Larsemann Hill (L=13; GEOG. 69.4°S, 76.2°E). It is located between Thala Fjord and Quilty bay, east of Stornes Peninsula in Antarctica.

Essentially, Earth’s ionosphere plays a vital role in the medium frequency (MF) and high frequencies (HF) radio communication [Little and Leinbach, 1959]. Radio waves transmitted from the Earth are reflected from the ionosphere and travel long distances, which provide a mode for communication. However, ionospheric absorption of radio waves is often the controlling factor for MF and HF radio communications. This is particularly important at high latitudes, where ionospheric storms frequently result in unreliable communications [e.g., Rourke, 1961]. The polar blackout phase or, periods of complete absorption of MF and HF radio signals due to ionospheric storms may last for many hours, and over a period of a month. In addition to that, it may also reduce the signal in-time by more than 20 percent [Detrick and Rogenberg, 1990]. Studies of ionospheric absorption of radio waves are thus of considerable interest to the communication engineers and space researchers.

Approximately, five to six decades ago, ionospheric absorption measurements were depended upon the study of man-made radio waves reflected back to the earth from the ionosphere. These techniques, although highly valuable, are laborious, and fail completely at high latitudes during polar blackouts. Mitra anid Shain [1953] introduced for the first time so-called cosmic noise method, in which ionospheric absorption is measured by comparing the signal strength of extraterrestrial radio waves will be received on a fixed-receiving system with the signal strength received on the same system at the same sidereal time under conditions of negligible ionospheric absorption.

With the time progress, cosmic noise technique was highly admired for absorption work at high latitudes; by a suitable choice of observing frequency, absorption can be measured even during polar blackouts. The cosmic noise method was an obvious choice for an IGY multi-station investigation of high latitude ionospheric absorption and special receiving equipment,
described in detail in this chapter. So requirement of an instrument to monitor the lower ionosphere was unavoidable. Use of wide beam Riometer has been used for this purpose since 1950s. Basically, **Riometer** is the acronym of Relative Ionospheric Opacity Meter using Extra Terrestrial Electromagnetic Radiation. It is an important ionospheric diagnostic tool which uses the randomly fluctuating, almost white, noise from galactic radio sources as probing signals to investigate the upper, ionized part of the Earths atmosphere [Little, 1954; Little and Leinbach, 1958, 1959]. Outside the influence of the Earths environment these radio signals have fairly constant intensities [Stauning, 1984]. Absorption of the cosmic radio signal is experienced due the ionosphere at frequencies above 15 MHz when highly directional antennas are pointed towards the particular part of the sky. Celestial objects like Quasars, super dense objects that lie far from Earth, emit electromagnetic waves in its entire spectrum including radio waves.

For last two decades, use of Imaging Riometer for high latitude ionospheric study has been quite popular among polar researchers [e.g., Detrick and Rogenberg, 1990; Hargreaves et al., 1991]. Important studies have been carried out using Riometer data to probe the ionospheric conditions in addition to their relation with space weather events. The first detailed paper by Ansari [1964] showed simultaneity of occurrences of radio wave absorption and visual aurora which is a manifestation of energetic solar wind particles precipitation into the high latitude ionosphere. At high latitudes two main types of absorption events seen in Riometer measurements: (1) the auroral absorption (AA), caused by precipitating magnetospheric electrons and (2) polar cap absorption (PCA), caused by flare-associated solar energetic ions. Magnetospheric particles in the 0.5-20 keV energy range precipitating in the ionospheric E- and F-regions are mostly responsible for the visual aurora, which are extensively studied with ground- and satellite-based optical instruments. [e.g.,Kellerman, 2009; Frey et al., 2004]. More energetic electrons (> 20keV) enhance the electron densities in the lower E- and D-regions (< 100km) of Ionosphere. Walker and Bhatnagar [1989] confirmed experimentally that auroral absorption and electrical conductance are closely related. Moreover, CNA depends indirectly on the electric field. These characteristics are observed
when strong electric fields drive plasma waves that in turn interact with electrons increasing their temperatures and effective collision frequencies [St.-Maurice et al., 1981; Schlegel and St.-Maurice, 1981].

2.1.1 Indian perspective of Ionospheric study using Cosmic Noise Measurements

Indian contribution to the study of cosmic noise started six decades ago. Mitra and Shain [1953] introduced cosmic noise method for the first time. The ionospheric absorption was measured by comparing the signal strength of extraterrestrial radio waves received on a fixed receiving system with the signal strength received on the same system at the same sidereal time under conditions of negligible ionospheric absorption. Bhonsle and Ramanathan [1958] reported absorption in the D-region over Ahmedabad, India by using riometer at 25 MHz. Occurrence characteristic of ionospheric absorption in the time period from afternoon to evening is consistent with the daily variation of the ionospheric F-region absorption associated with increases of foF2 which were obtained from the statistical analysis of the riometer absorption on 25 MHz at Ahmedabad in India (Abdu et al., 1967). Diurnal and seasonal variation of total ionospheric absorption (L) at an equatorial station, Trivandrum ($dip\,0.6^\circ$ S, geographic long $76.56^\circ E$) has been studied using two years riometer data [Parameshwan et al., 1976]. They have investigated the dependence of L on geophysical parameters and sunspot numbers. In addition to that, they have estimated the electron temperature of F-region from the F-region contribution to the total absorption. Lunetta and Abdu [1971] suggested that the absorption of cosmic radio noise varies with the latitude of the observations.
2.1.2 The principles of cosmic noise absorption process

Absorption largely occurs in the D-region of the ionosphere, which is that region between heights of approximately 60 and 100 km above the surface of the earth. The highest concentration of gas molecules can be found within this part of the Ionosphere. Should any free electrons be present in the region, their motion will be affected by absorbed energy from a propagating radio wave. If the electrons collide with neutral atoms or molecules then energy will be lost to the heavier particle. Absorption of the wave has occurred. Under quiet geomagnetic conditions, and at middle and low latitudes, D-region ionization is a daytime effect produced by solar ionisation of the gas molecules, and recombination takes place at night to form a unionized region, largely transparent to HF radio waves. Under geomagnetically disturbed conditions energetic electrons can enter the D-region at high latitudes and produce additional ionization which causes absorption. This is auroral absorption (AA), which maximizes generally in the auroral regions. Polar cap absorption, or PCA, on the other hand, is produced by strong D-region ionization resulting from an influx of energetic protons, usually after a major solar flare. This effect can extend over the whole of the polar caps, hence the name, and can cause severe absorption, the effects of which may last for a week or more and prevent all HF-communications in the Polar Regions. Neglecting the effect of the earth's magnetic field, auroral absorption can be shown to depend on radio frequency as

\[ A(dB) = 4.6 \times 10^{-5} \int \frac{N_e \nu dl}{\nu + (\omega \pm \omega_H \cos \theta)^2} \]  

(2.1)

Where, \( N_e \) and \( \nu \) are respectively the local electron density and collision frequency, \( \omega_H \) is the electron-gyro frequency. The + and - signs indicate the two different types of polarization of the incoming wave. \( \omega \) is the angular frequency of the wave propagating at an angle \( \theta \) with the geomagnetic field along the path \( l \) of which \( dl \) is the small element.

The effective electron collision frequency can be derived with the use of Maxwellian distribution function and can be written as [Aggrawal et al., 1979],
CHAPTER 2. imaging Riometer at Maitri, Antarctica

\[ V_{eff} = \frac{\int_{v=0}^{\infty} \sum_{n=1}^{N} \sigma_{n}^{m}(v) v F(v) dv}{\int_{v=0}^{\infty} F(v) dv} \]  \hspace{1cm} (2.2)

where, \( \sigma_{n}^{m} \) is the velocity dependent cross-section for momentum transfer during electron collisions with species (electrons or, ions).

2.1.3 Advantages and essential features of an imaging Riometer

Advantages of imaging Riometer over simple riometers are quite significant. Basically wide-beam Riometers consist of simple antenna array system with an azimuthally symmetric radiation pattern. So, they have wide field of view (FOV) but no imaging capability. The antenna is connected to a receiving device which measures the power of the incoming signal (cosmic background noise). In the absence of geomagnetic activity the received power forms a baseline, or quiet day curve from which absorption measurements can be derived. They are useful for a general overview of the current state of the ionosphere, but do not provide any information on the spatial structure and dynamics within their field of view. An imaging Riometer consist of dipole antennas configured as filled phased array [Mailloux, 2005] and a modified two dimensional Butler matrix [Butler et al. 1961]. Hence it can produce multiple imaging beam with better resolution. Therefore, high energetic particle precipitation and their spatial and dynamic structure can be studied using imaging Riometer. Cosmic noises received by imaging Riometer are in the radio wave frequency range well above 15MHz [Mitra and Shain, 1953]. These radio waves propagate continuously towards the Earth. While coming in, noises have to propagate through the height integrated ionosphere. During geomagnetic disturbed time, these radio waves undergo attenuation due to enhance ionization and collision frequency in the ionosphere. Sen-Wyller formalism [Sen and Wyller, 1960] provides the most complete theoretical treatment for the propagation and attenuation of radio waves. However, the typical frequency at which Riometer operates, is much higher than the plasma frequency, so Appleton-Hartee formulae are good approximations and provide a well established relation among the various ionospheric parameters such as collision frequency, gyro-frequency
etc with radio wave absorption in dB.

### 2.1.4 Installation of imaging Riometer at Maitri

The first imaging Riometer system (with 49 beams) was installed at South Pole station in Antarctica in 1988 by the University of Maryland group [Detrick and Rosenberg, 1990]. Then just after six years, there were around six additional imaging Riometer installations with varying beam dimension of 8 x 8 or, 4 x 4 beams.

![Image of imaging Riometer at Maitri](image)

Figure 2.1: imaging Riometer at Maitri

A state of the art 38.2 MHz imaging Riometer was installed at Maitri during the austral summer of 2009-2010. Figure 2.1 is showing the south-east view of the installed imaging Riometer at Maitri. It includes the antenna and the hut (yellow color hut) where the receiver unit is
kept. This system consists of 16 (4 x 4) crossed dipole antennas that can be upgraded to 64 (8 x 8) dipole antenna system at a later stage. The field of view (figure 2.2) of this system at 90 km altitude is 200 km x 200 km with time resolution of 1 second.

![Figure 2.2: Field of View of imaging Riometer](image)

The operation of the Riometer is mainly controlled by the Advanced Riometer component (ARCOM) software provided by Lancaster University, UK, which is the solo responsible for starting and stopping of data recording, selection of files etc. The complete analysis, starting from the generation of standard quiet day curve(QDC), their checking of validation to the absorption plot, keogram as per the demand can be controlled by a software called Multi Instrumental Analysis (MIA), which is developed by manufacturer at Lancaster University, UK [Honary et. al.,2011].
Figure 2.3: Shematic diagram of operation

Generally, the imaging Riometer system uses an array of $N^2$, where $N=2^m$; $(m=1, 2, 3, 4)$ identical antenna elements, such as simple or crossed dipoles, placed in a square grid over a common ground plane. Typically the separation of elements would be $0.5\lambda$, where $\lambda$ is the wavelength, while their heights above the ground plane would be $0.25\lambda$. The $N^2$ antenna elements are coupled via cables of identical electrical lengths to a so-called Butler matrix [Butler and Lowe, 1961]. The beam-forming Butler matrix consists of power divider and adder hybrids and phase shift elements. It divides and combines the signals from the $N^2$ inputs to the $N^2$ outputs, such that all input terminals are connected to each output terminal with systematically varying phase shifts. For a given geometry of the antenna array, the phase shifts at each output terminal adds to the phase of the signals arriving from a specific direction in space. The $N^2$ output terminals are connected to Riometer channels, where each Riometer channel acts as an ordinary Riometer receiver. In most applications the channels are grouped, and commutated within each group, in order to reduce the number of Riometer instruments required.
2.1.5 Importance of operating frequency of imaging Riometer

As already mentioned in section 2.1.4, the imaging Riometer at Maitri is being operated at 38.2 MHz. While choosing suitable operating frequency for riometer, several points have been taken in to consideration. First, the cosmic noise should not be significantly deviated in path by the ionosphere, hence the operating frequency must be well above the penetration frequency of the ionosphere must be used. Secondly, the frequency dependence of the absorption must be considered: one can detect small variations in absorption level as well as the major absorption events. If the frequency is too high the absorption range will be small and the measurement may not able to detect small and yet important variations. Small variations includes pulsations which are likely to occur during geomagnetic pulsations. A brief description is mentioned in the introduction. However, if the frequency is too low then 'black-out’
conditions may occur, in which the incident power drops below the minimum resolvable level of the system. Thirdly, we have to consider interference. Since imaging Riometer at Maitri measures very low signal powers (down to -150 dBW or less), manmade interference is a big issue. Interference levels can be high in the HF range due to ionospheric propagation, and this is another reason for picking a frequency well above the penetration frequency. For high-latitude work, frequencies in the 30-50 MHz range are now the most popular, as they satisfy the above requirements rather well, though propagated interference can still present. However, the major limitation of the operating frequency of the imaging Riometer at Maitri appeared while observing the x-ray flare signatures in the Riometer data.

The phenomenon of a sudden increase in the strength of the visible \( H - \alpha \) line is known as a solar flare. It releases the built up magnetic energy during reconnection. Intense solar flares are frequent during solar maximum period of the 11-year solar cycle. Flares produce radiations throughout the electromagnetic spectrum with different intensities. Radiation is emitted across the entire electromagnetic spectrum, from radio waves at the long wavelength end, through optical emission to X-rays and gamma rays at the short wavelength end. Flares are classified as A, B, C, M, X according to the order of magnitude of the peak burst intensity \( I \), measured at the Earth in the 0.1-0.8 nm wavelength band. M-class flares can cause brief radio blackouts at the poles and minor radiation storms that might endanger astronauts. The most intense flares of class X can wallop the Earth with radiation that interferes with radio, GPS systems and power grids.

Solar flare has a great influence on the Earth upper atmosphere and ionosphere. During a flare, the extreme ultraviolet EUV and Xrays ionize the atmospheric neutral compositions in the altitudes of ionosphere to make the extra ionospheric ionization that causes many kinds of sudden ionospheric disturbance phenomenon (SID), such as sudden phase anomaly (SPA)(Ohshio, 1971), sudden cosmic noise absorption (SCNA), sudden frequency deviation (SFD)(Donnelly, 1969; Liu et al.,1996), shortwave fadeout (SWF)(Stonehocker, 1970), solar flare effect (SFE) and sudden increase of Total Electron Content (SITEC) (Donnelly, 1969;
Mitra, 1974; Garriott et al., 1967; Zhang and Xiao, 2005). Enhanced X-ray and extreme ultraviolet (EUV) irradiate during a solar flare causes increased ionization in the lower ionosphere (D and E regions) all the way up to the F region, depending on the flare spectrum. The increase of electron density in the F region is responsible for the increased Total Electron Content (TEC) (Mendillo et al., 1974). There have been some studies on ionospheric response to solar flares on different planets (Mendillo et al., 2006).

Bhonsle R.V. (1960) studied sudden cosmic noise absorption (SCNA) at Ahmedabad, India (23.03° N, 72.63° E; low latitude) on 25 MHz associated with solar flares. Shain and Mitra had analysed the SCNA observed on 18.3 MHz in Australia. Bhonsle found that SCNA at 25 MHz recorded at Ahmedabad have been markedly larger in size and duration than those observed in Australia.

Flare photons travel directly from the flare site to the Earth, creating ionization in the dayside atmosphere/ionosphere primarily at the subsolar region. Generally, the more energetic photons cause ionization deeper in the atmosphere. The photons traverse the 1 AU distance in 8 min. Flares last from ~ 30 min to ~ 1 h, so the resultant ionization continues throughout the event. Flare energetic particles arrive shortly after the flare photons. The time delay depends on the particle’s kinetic energy, pitch angle, and magnetic connectivity. The particles enter the polar ionosphere. The more energetic particles penetrate deeper into the atmosphere. Owing to the thickness of the atmosphere and the grazing angle of incidence at the poles and the terminators, lesser ionization occurs in these regions than at the subsolar point.

Thus, in flare studies from ground observations, latitude of the location is also important. Flare studies so far are done from low-latitude locations. Ionospheric effect of solar flare using imaging riometer at high latitude was first of its kind.

For Cosmic Noise Absorption (CNA) observations, data from imaging riometer at Maitri, Antarctica has been used. The imaging riometer was installed at Maitri station in the austral
summer of 2009-2010. Data is unavailable for two years 2012 and 2013, thus period chosen for this study is 2010, 2011 and 2014. To study the response of ionosphere to the solar are, we have used X-ray data from GOES (GOES-14 and GOES-15) satellites. The SEM XRS system of each GOES satellite consists of two ionization chambers, one of which is Xenon-filled with Argon and covers the nominal wavelength range. Flares are classified according to the order of magnitude of the peak burst intensity ($W/m^2$), measured at the GOES X-ray detector in the 0.1-0.8 nm wavelength region. Datasets were taken from National Oceanic and Atmospheric Administration (NOAA), which are available at (http://satdat.ngdc.noaa.gov/sem/goes/data/). Study period were 2010, 2011 and 2014. 24th solar cycle began on January 4, 2008. Generally, first three years of a solar cycle show low solar activity and it is termed as solar minimum. Thus it was a low solar activity period till February,2011. Therefore, the first time slot ere taken to be January, 2010 to February, 2011. Second time slot will be March, 2011 to December, 2011 and January, 2014 to December, 2014. For 2011 and 2014, GOES-13 as well as GOES-15 data are available. Thus, for each month, satellite was decided at first and the X-ray ux ($W/m^2$) data of corresponding satellite was obtained from NOAA website. A typical plot would look like Figure ??.

![Figure 2.5: X-ray Flares presented in XL and XS band for the month of February, 2011](image-url)
CHAPTER 2. imaging Riometer at Maitri, Antarctica

Figure 2.6: X-ray Flares presented in XL and XS band for the month of February, 2011

Total 34 solar flares were observed during January, 2010 to February, 2011 out of which 1 is X-class and 33 are M-class flares. After the time criterion is set, total 9 ares are obtained, all of which are M-class. The time criterion is that we only count flares those occur with in 0900-1500 UT in order to see maximum flare effect. Similarly, Total 97 flares are observed during March, 2011 to December, 2011 in this duration. 7 are X-class while 90 are M-class flares. In the selected time window, 27 flares are obtained with 3 X-class and 24M-class flares. In January, 2014 to December, 2014, we have observed 16 X-class and 164 M-class, a total of 180 flares. The flare statistics are given in the figure.

Figure is showing the occurrence of a M-class flare during August 03, 2011. The onset of flare event was at approximately 1349 UT (1436 LT for Maitri). This event was detected by GOES-15 satellite data. The lower panel of Figure shows the riometer signal data during the particular solar are event. There are 16 colour lines corresponding to 16 different beam signals of the imaging riometer installed at Maitri. No CNA has been observed during the onset of M-class are mentioned above. CNA is essentially calculated by subtracting the quiet day signal of riometer from the event day signal. If at all there is any depression in
the riometer signal data, that signifies the enhancement of electron density \((N_e)\) in the D-region of ionosphere. Hence, no depression in the riometer signal during the solar flare event of August 03, 2011 defines two things. Either there is very little difference between the temporal enhancement of ionisation with the background ionisation medium over Maitri which is a high latitude station or ionisation produced by the M-class flare is not sufficient to alter the riometer signal at 38.2 MHz.

Figure 2.7: M6.1 Flare event on 03 August, 2011 and corresponding CNA signature

To validate the observation, we have shown another X-class flare event observed by GOES-15 satellite data and riometer signal data of Maitri during 09 August, 2011 in Figure ?? . Similar to Figure ??, we see no alteration in the signal data during the X-class flare which occurred at
No alteration of the riometer signal due to any kind of solar flare event right from C-class to X-class flares is evident in this statistical survey. In this context, the proper selection of the events have been taken care such that Maitri should not be in the night side during any selected event. The possible causes of no CNA due to solar are are the location of study and the operating frequency of the riometer. It seems that temporal ionization enhancement due to solar flare is not significant compared to the background ionization density at Maitri. In addition to that the collision frequency at high latitude is less as compared to low latitude and equatorial region which reduces the probability of CNA at high latitude. Moreover, the operating frequency of the riometer is almost double of the frequencies used in previous studies of solar are events. Hence we conclude that it is difficult to get any signature of solar are in the riometer data with operating frequency of 38.2 MHz at the location of Maitri. We are trying to carry out further
TEC measurements during the selected solar are events which may give a hint of temporal ionisation enhancement due to solar are events. In addition to that we are trying to explain this observation theoretically.

2.2 **Quiet day curve and validation of imaging Riometer data set**

The raw or received imaging Riometer data are in .arcom format. The .arcom format is customized form of binary format. In order to get the ASCII data, one has to use the MIA software. MIA software gives ascii data of two different kind of beams. The ASCII data matrix given by MIA software for one day is $32 \times 86400$. The time series plots of raw data are given in figures 2.5 (1) and 2.5 (3). It can be seen that raw data are extremely noisy. The reason for such noisy data is the sensitivity of the instrument, as it receives data in milli-watt power. These noisy data are processed with outlier method in order to get smooth signatures, examples are shown in figures 2.5 (3) and 2.5 (4). All the matlab programs for further analysis of imaging Riometer data which includes removal of noise and smoothing of data sets, wide beam signal strength calculation, keogram formation, ULF waves detection etc are indigenously developed at Indian Institute of Geomagnetism by me and my Guide Dr. Ashwini K. Sinha and Mr. Rahul Rawat (Technical officer-II).

2.2.1 **Technique for deriving QDC**

The method of determining QDC of cosmic noise signal has been discussed extensively by several authors [e.g., Mitra and Shain, 1953; Lusignan, 1960; Steiger and Warmick, 1967; Armstrong et al. 1977; Krishnaswamy et al.,1985; Tanaka et al., 2007, etc]. Recently, Moro et al, [2012] have presented new modified technique for Riometer Network (SARINET) data
from South America with respect to method adopted by Tanaka et al., [2007]. Here, two criteria have been used: (1) Riometer data selection according to the geomagnetic activity and (2) data cleaning with respect to electromagnetic interference as well as other unwanted noises.

In the current approach for deriving QDC of cosmic noise signal, we have used two criteria as followed by Moro et al.[2012]. For fulfillment of the first criteria, the average of imaging Riometer data for the five international quietest days was used to derive QDC for a particular month. Table ?? is showing the list of days taken in a month during the year 2010-2011 for deriving QDC. It should be noted that only 6 days data were available during December, 2010, out of that only one day was magnetically quiet(Kp < 3). The second criteria are taken for removing electromagnetic interference. This may be produced due to presence of man-made interference or solar noise bursts. These bursts can affect the estimation of the QDC leading to an increase of the QDC level. [Moro et al, 2012]. Here, we have taken the selected days for the year 2010 and 2011 confining to quietest days of month. The error limit of QDC curve ranges from 0.02 dB to 0.30 dB. The maximum error value has been recorded in January
month and minimum in the September month. Since imaging Riometer can serve both the narrow beam application as well as wide beam application, we have chosen the solar zenith corrected wide beam data for this study. The imaging Riometer data set has inbuilt provision to differentiate wide beams and narrow beams. In figure ??, QDC of each month have been plotted.

2.2.2 Sidereal time and Monthly variation of QDC at Maitri, Antarctica

The signal strength of radio noises, coming from the inter-stellar space varies with sidereal time (time scale based on earth's rate of rotation measured relatively to fixed stars) and months. In general, average sidereal day is of 23 hr 56 min and 4 seconds whereas the solar day is of 24 hrs. So there is an approximately 4 minute difference between sidereal and solar day. Imaging Riometer data is in solar time format or UT format. While deriving QDC, with respect to solar time, we would expect a shift of about 2 hr (30days X 4 min) in the diurnal pattern of signal strength between consecutive months. This seems to be a genuine tool to assess the accuracy as well as the correctness of data and thereby validating the new dataset.

We observed an approximate shift of around 2 hr in the consecutive months that can be seen in figure ???. In January, the maximum value of the signal strength has been obtained at around 0900 UT, whereas in February month, the occurrence time of maximum value has shifted around 0700 UT. Similarly for other months, the shift of 2 hrs is consistently observed. Moreover, if one follows the red tone which represents the maximum strength of QDC, around 2 hr/month shift is consistently observed.

In quiet conditions of ionosphere over the station of Maitri, cosmic noise signal has a regular diurnal pattern (figures ?? and ??). However, sun can also influence the level of signal through following mechanism. The ultraviolet rays of the sun enhances the ionization of the ionosphere which ultimately causes more absorption of signal of cosmic noises even in a quiet day, when there is no additional input of particle flux from the magnetosphere, e.g., during
Figure 2.10: Quiet Day Cosmic noise signals or, Quiet day curves(QDCs) for each months of year 2010-11. Here wide beam(beam 17) data of imaging Riometer was used for deriving QDCs
Table 2.1: List of number of quiet days considered for QDC analysis of cosmic noise signal. Continuous 12 months period of imaging Riometer data have been taken from November, 2010 to October, 2011. This period is taken as per the data availability and quality.

<table>
<thead>
<tr>
<th>Year</th>
<th>Months</th>
<th>No. of days</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>November</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>January</td>
<td>4</td>
</tr>
<tr>
<td>2011</td>
<td>February</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>March</td>
<td>5</td>
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<td></td>
<td>April</td>
<td>5</td>
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<td>May</td>
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<td>June</td>
<td>5</td>
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<td></td>
<td>July</td>
<td>4</td>
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<td></td>
<td>August</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>October</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 2.11: Contour plot for Sidereal shift of maximum signal strength of Cosmic noise signal for consecutive months. For the month January to May, shift of 10 hours (10 UT to 00 UT) of maximum signal strength is seen. Similarly, for the month June to December, shift of 14 hours (24 UT to 10 UT) is seen.
substorm phenomena [Browne et al., 1995]. At Antarctica, seasonal variation of strength of quiet day curves of cosmic noises has been observed. Figure ?? shows a seasonal variation of the cosmic noise signal strength. In three panels, average strength, maximum strength and minimum strength of the QDC of cosmic noise signal for each month have been plotted respectively. There is comparatively maximum drop of signal strength (average, maximum and minimum) in the month of March (autumn equinox month) and August (pre-spring equinox month).

However, the average strength of cosmic noise signal is maximum ( -112.03 dB) in the month of May, which is in winter season and ( -111.95 dB) in December month in summer at Antarctica. From Equation (1), one would expect higher cosmic noise signal strength during winter (no-Sun) months when ionospheric conductivity is less and opposite for summer (sunlit) months. However, in our observation, we see very complex behavior of signal strength variation over months (Figure 4). When austral winter approaches (March onwards) signal strength rises (as expected), whereas for the rest of the months variations are quite random. For example, sudden drop in signal strength from January to March (summer season), May to June (winter in progress) and relatively constant variation till the commencement of austral summer and further increase cannot be explained on the basis of solar illumination. It makes us to believe that other factors significantly contribute towards the seasonal variation of signal strength of QDC.

2.3 Initial observations

Below figure ?? shows the typical plot where cosmic noise signal strength and degree of absorption observed at Maitri. In the upper panel, the red curve represents the five quiet day average plot together with the signal strength plot on 03 April, 2011. One can clearly see the dipping of signal strength for the day of 03 April, 2011 on many occasions. The lower panel of figure ?? shows the CNA events on 03 April, 2011. Hence, CNA on a particular day can be
Figure 2.12: Seasonal variation of cosmic noise signal strength: Upper, middle and lower panels are respectively for average, maximum and minimum strength value.
In equation (2.3), $I_{\text{eventday}}$ is the riometer signal strength of a day of any month and $I_{\text{qdc}}$ is the average of quiet day signal strength of that month, when the event day fall in. Choosing the quiet day curves (QDC) of Riometer data needs to be done carefully. The details of choosing QDCs is already explained in the previous subsection. Generally, ionospheric absorption measurement in Riometer is made with respect to vertical incident signal, because absorption may increase with increasing elevation angles. Figure (2.10) shows the corrected obliquity factors with respect to elevation angle [Browne et. al., 1995].
Figure 2.14: Obliquity factor with respect to elevation angles [Browne et al, 1995]
2.3.1 Data sets

In order to provide some of the initial results using imaging Riometer data from Maitri as a result of different kinds of geomagnetic activities, we have used multi instrumental datasets. For CNA observations, we have taken data of imaging Riometer which is installed at Maitri. The stability and correctness of data obtained from imaging Riometer has been tested and explained and these are the first results. In addition to imaging Riometer, we have used magnetic field data. Indian Institute of Geomagnetism has been operating a digital fluxgate magnetometer (DFM) at Indian Antarctica station, Maitri since 2003. The magnetic field components at Maitri sampled at 1-second intervals has been used in this study. In addition to that, data sets were taken from World Data Centre (WDC), Kyoto (http://wdc.kugi.kyoto-u.ac.jp/) for auroral electrojet (AE) index and symmetric-H (SYM-H) index. Interplanetary magnetic field (IMF) and solar wind data such as solar wind velocity, recorded by instruments aboard ACE satellite were made available by CDAWeb (http://cdaweb.gsfc.nasa.gov/).

2.3.2 Keograms for different geomagnetic activities

In this section, CNA characteristics during storm time substorm and non-storm substorm occurring near midnight hours at Maitri on 12 April 2011 and 09 July 2011 respectively have been presented. We observe that Maitri comes under the influence of westward electrojet for both the events. However, there is a subtle difference to note between these two events. Additionally, a day side CNA (DCNA) event occur during 06 April 2011 has also been presented. The detail characteristics of DCNA events are extensively discussed in chapter 4 of this thesis. In the end, the local time distribution of the CNA events is shown and discussed.
CNA during the storm time substorm (12 April 2011)

Cosmic noise absorption (CNA), in association with the magnetospheric substorm occurred during 0600-0800 UT on 12 April 2011 has been shown. For this event Maitri station would lie in 0500-0700 MLT interval as \((MLT = UT - 1)\) for our station. In figure??, we depict the interplanetary magnetic field (IMF) and solar wind velocity as observed by instruments aboard ACE satellite located outside of the Earths magnetosphere (at \(X = 229.6\) Re, \(Y = - 21.5\) Re, \(Z = - 40.9\) Re in GSM coordinate system: here Re is the radius of the earth \(6378\) km). In order to corroborate the interplanetary observations with ground magnetic data, IMF and solar wind data have been delayed by 60 minutes taking into account the travel time of solar wind at an average speed of \(500\) km/s from the location of the satellite to the magnetopause of the earth. The upper first two panels represent the IMF Bz and solar wind velocity \((V_s)\) respectively. In the next two panels, SYM-H and AL-index have been plotted respectively. The bottom four panels represent the H-component of geomagnetic field, cosmic noise signals, relative CNA and image of CNA over Maitri station. In the sixth panel, quiet day signal of April month and signal of individual day (12 April 2011) has been plotted. We obtained CNA (the bottom most panel) for the day by taking difference of cosmic noise signal of that day in a month from the QDC of the same month.

The onset of substorm can be clearly seen at \(\sim 0600\) UT in the AL-index with a sharp depression of \(\sim -1000\) nT. This appears to be a storm time substorm event as the SYM-H index value has gone down to -50 nT [Hsu et al, 1998]. The solar wind velocity on that particular day was high \((\sim 500\) km/sec\) and steadily increased up to 550 km/sec. The solar wind velocity was steady during all the phases of substorm. The Substorm triggering initiated with sharp southward turn of IMF Bz at \(\sim 0500\) UT. It remained southward for 5 hrs then turned northward at 1010 UT approximately. At the onset of substorm, simultaneous occurrence of westward electrojet and cosmic noise absorption (CNA) has been observed over Maitri. Intensity of the westward electrojet is weaker over Maitri \((H\ depression \sim -350\) nT\) than what is observed in
CHAPTER 2. imaging Riometer at Maitri, Antarctica

Figure 2.15: (form top to bottom) Bz component of interplanetary magnetic field (IMF), solar wind velocity (Vs) as observed by ACE satellite, Sym-H index, AL index, geomagnetic H-component variation, cosmic noise signal power (red line indicates the signal strength of 12 April 2011, where as the black line indicates the quiet day signal for the April month), CNA and image of CNA at Maitri station. Interplanetary observations are delayed by 60 min to compare with the ground data. This event represents the CNA during storm time-substorm. Correlation coefficient between H-component and CNA in this case is high \( r = -0.88 \)
the AL index. This could be due to the fact that Maitri station was around 0500 hr MLT and quite away from the center of the westward electrojet which peaks around midnight [Allen and Kroehl, 1975; Singh et al., 2012]. Moreover, due to the absorption of cosmic radio signal, it was attenuated by more than 1.5 dB in comparison to monthly QDC (see bottom panel of Figure2). It should be noted that the correlation coefficient (r) between H-component and strength of CNA during the event (0500-0700 MLT) at Maitri for this event is very high (r= -0.88).

![Figure 2.16: Keogram or image plot of CNA during 12 April 2011](image)

Figure 2.16: Keogram or image plot of CNA during 12 April, 2011

Figure ?? shows the image plot of CNA during the event. It has been observed that CNA become more intense during the period of 0630-0730 UT. It almost cover the whole latitudinal range cover by the field of view of imaging Riometer. The maximum CNA enhancement seems to be localized to equatorward i.e in figure ??, one can max. CNA is seen at ∼ 61 CGM-lat.

**CNA during non-storm time substorm event (09 July 2011)**

On 09 July 2011, we observed a substorm during 0300-0500 UT which is not accompanied by storm. For this event, Maitri station would be in the post-midnight hour (0200-0400 MLT).
Top two panels of figure ?? depict the IMF Bz and solar wind velocity (Vs) as observed by instruments aboard ACE satellite. During this event the location of ACE was at $X = 237.9$ Re, $Y = 40.4$ Re, $Z = 23.0$ Re in GSM coordinate system. In order to relate the interplanetary observations with ground magnetic data, IMF and solar wind data have been delayed by 71 minutes taking into account the travel time of solar wind at an average speed of $\sim 340$ km/s from the location of the satellite to the magnetopause of the earth. In the next two panels, SYM-H and AL index have been plotted respectively. The bottom four panels respectively show H-component of geomagnetic field, Cosmic noise signals, relative CNA and image of CNA respectively at Maitri. In the sixth panel, quiet day signal of July month and signal of 09 July 2011 has been plotted. We obtained CNA (the bottom most panel panel) for the day by taking difference of cosmic noise signal of that day in a month from the QDC of the same month.

Generally, non-storm time substorms have no sign of simultaneous storm [Hsu et al, 1998]. At the time of onset ($\sim 0300$ UT) of substorm the sym-H index was 1 nT, which clearly shows no signature of enhancement of ring currents. The magnitude of AL-index was $\sim 700$ nT. Simultaneous observation of solar wind velocity for ACE satellite showed steady and slow flow of solar wind having velocity $\sim 340$ km/s with southward IMF Bz. This non storm time substorm led to a less amount of absorption of cosmic noise ($\sim 0.4$ dB) along with almost same magnitude of westward electrojet (-350 nT) despite the fact that AL-index was less ($\sim 700$ nT) as compared to storm-time substorm of 12 April 2011 seen over Matri station. This is for the reason that Maitri was at around 0200 hr MLT and relatively nearer to the centre of westward electrojet (discussed earlier in the figure 5). The correlation coefficient between H-component and strength of CNA during the event (0200-0400 MLT) at Maitri in this case was found to be less ($r = -0.53$) as compared to storm-time substorm case of 12 April 2011. However, we obtained better ($r = -0.75$) when we restrict the calculation of correlation coefficient within the time limit (0200-0330 MLT). This time limit has been taken due to the fact that CNA lasts for this period of time only during the event.
Figure 2.17: (form top to bottom) Bz component of interplanetary magnetic field (IMF), solar wind velocity (Vs) as observed by ACE satellite, Sym-H index, AL index, geomagnetic H-component variation and cosmic noise signal power (red line indicates the signal strength of 09 July 2011, where as the black line indicates the quiet day signal for the July month), CNA and image of CNA at Maitri station. Interplanetary observations are delayed by 71 min to compare with the ground data. This event represents the CNA during non-storm time substorm. Correlation coefficient between H-componet and strength of CNA in this case is less ($r = -0.53$).
Figure 2.18: Keogram or image plot of CNA during 09 July, 2011

Figure ?? shows the image plot of CNA during the event. It has been observed that CNA become more intense during the period of 0340-04310 UT. However, it is not significantly strong as earlier event shown in figure ???. It is also very localized to $\sim 62$ CGM-lat. Hence, the level of activity decides the CNA occurrences. However there are many more factor which control CNA production are thoroughly discussed in forth coming chapters.

**Day side cosmic noise events (06 April 2011)**

Not only production of CNA is localized to mid night and morning side, sometimes, it also occur during day side. On 06 April 2011, couple of intense CNA occurrences can be seen. Figure ?? shows the north-south and east-west keogram of CNA production during 06 April, 2011. Some times these CNA are larger than the morning time CNA. These are mostly occur during intense to moderate type geomagnetic storm and are related to particle precipitation due to various types of wave particle interactions. A detail study is shown in chapter-4 and 5.
Figure 2.19: North-south and East-west Keogram or image plot of CNA during 06 April, 2011

2.3.3 LT distribution of CNA events at Maitri

This section has been dedicated to discuss the dominant mechanisms for the production of CNA at Maitri. In order to do so, we have examined local time distribution of CNA occurrences at Maitri. Figure ?? shows the pie chart of the occurrences of CNA. Firstly, criteria were adapted to define a CNA event. The detail description of the criteria has been given in chapter 3, section 3.2. Imaging Riometer data for the year 2011 was taken to find the statistics. There are more than 100 events were detected. For the convenience, a day of 24 hours is divided into 4 sectors i.e. day (09-15 LT), night (21-03 LT), dusk (15-21 LT) and dawn (03-09 LT) for Maitri as seen in figure ???. Maximum occurrences is seen in the dawn
Figure 2.20: LT distribution of CNA events

sector. Day and night sector have almost similar occurrences of CNA and least occurrences can be seen in dusk sector. This signify the most dominant mechanism for the production of CNA is susbtorm.

2.4 Discussion and Conclusion

For the first time, data of imaging Riometer at Maitri, Antarctica have been used to study the different types of CNA occurrences and their characteristics during various space weather activities such as geomagnetic storm, magnetospheric substorms and solar flares. The observation of CNA using Imaging Riometer could be a great asset for carrying out the research in sub-auroral ionosphere. The usefulness of this instrument is remarkable in understanding of precipitation dynamics due to substorm processes at sub-auroral latitude region. In this paper we have given a brief account of the background, theory and instrumentation with an emphasis on validating the newly obtained data set.

The quiet day curve (QDC) of any new instrument is most essential part of study. One has to
understand the daily and seasonal variation of QDC of new instrument for further research. So, here we have discussed about the sidereal and monthly variation of QDCs. A consistent sidereal shift of 2hrs in each consecutive month has been seen which signify the consistency and reliability of the new instrument. Thus, the shifting of the main source of the cosmic noise signal with sidereal time can be clearly identified. Monthly variation of cosmic noise signal in quiet condition i.e QDCs not only depends on the source of galactic cosmic noise but also on other factors. It seems other things such as orbital motion of the earth, the distance of the sun from the earth and level of ionization in the D-region during various months, responsible for cosmic noise during various months have simultaneous impact on the cosmic noise signal variation with months. Different cases of CNA during storm time and non-storm time substorms, both occurring in post midnight to early morning sector. Magnetic reconnection [e.g., Baker et al., 1996] and dipolarization/current disruption e.g. [Lui, 1998] in the near-earth magnetotail have been suggested as the cause of substorm expansion onsets. Initially it was suggested that storm and nonstorm time substorms are manifestation of different mechanism, namely magnetic reconnection and current disruption respectively [Baumjohan et al., 1996]. But later it was shown that storm and non-storm time substorms do not differ qualitatively in the generation mechanism [Hsu and McPherron, 1998]. Nevertheless, the energy accumulation and the dipolarization tend to be more significant during storm time substorms. Maitri is a sub-auroral station located in Antarctica and it is expected that the auroral oval would expand and cover Maitri location during disturbed days. Hence the station will come under the influence of Auroral electrojet. Here, during both the CNA events associated with magnetospheric substorm, the equatorward expansion of auroral oval has taken place. In case of CNA event occurring 12 April 2011 during storm-time substorm, the auroral electrojet was slightly stronger (AL 1000 nT) as compared with the non-storm time substorm event of 09 July 2011 (AL 700 nT). During both the substorms, clear influence of west ward electrojet of almost the same magnitude (350 nT) with simultaneous occurrence of CNA was observed over Matri. Maitri was nearer to the onset location of substorm of later case (09 July 2011- non-storm time) compared to that during 12 April 2011- storm-time, as the MLT range for
the event on 09 July 2011 was 02-04 hrs and it was 05-07 hrs for 12 April 2011. There are different kinds of CNA event depending on the local time and magnetospheric phenomena [stauning, 1994]. However the above two CNA events which have examined in this study, are confirmed to be associated with substorms. This kind of absorption is due to the precipitation of energetic electrons (energy range from 10 to 100 KeV) in the E-region and upper D-region (70-100 km) [kellerman, 2009]. While comparing the two events, we observed higher CNA for the storm-time substorm event. During storm-time substorm, the south-ward turning of IMF Bz occurred at around 0500 UT and was sustained up to 6 hrs. Moreover, the solar wind velocity (v) was high (550 km.) during the event. Thereby the convection electric field (-V X Bz) was stronger (5.5 mV/m.) and was sustained for longer period of time (6 hrs) which we can infer from the figure 5. One thing should be noticed in this storm-time substorm event is the difference of 01 hr between the south-ward turning of IMF Bz and onset of substorm. That means strengthening of convection electric field occurred much earlier (01 hr) that drove more flux of energetic charge particles in to the magnetosphere and caused subsequent loading of particles in to the magneto-tail region before the re-connection occur. Whereas, the other event of non-storm time substorm (figure 6) clearly shows weaker convection electric field (3.4 mV/m.) for lesser period of time (2 hrs). During this event the southward turning of IMF Bz occurred only 10 minutes before the onset of substorm and was sustained for comparatively less time (2 hr.) as compared to the storm-time substorm event. In addition to that, the solar wind velocity (V) was also moderate (340 km.) during this event. This clarifies that level of CNA is more related to loading of the particles and intensity of reconnection in the magnetotail. These results also strongly support the difference between storm-time substorm and non-storm time substorm characteristics stated by Hsu and McPherron[1998]. They clearly mentioned in their paper in 1998 that the energy accumulation and the dipolarization tend to be more significant during storm time substorms. Moreover, the reconnection of higher intensity also triggered a moderate storm which was associated with the 12 April 2011 event.

Finally, it can be concluded that depression in geomagnetic H-component and CNA at Maitri
are the consequences of flux of electrons intensifying the auroral electrojet and precipitation of electrons enhancing the conductivity of the upper D-region respectively. The correlation coefficient between H-component and CNA strength at Maitri is -0.88 for storm time substorm event and it is -0.53 for non-storm time substorm event. Correlation coefficient for both the events are significant as enough number of data points (7200) have gone in to the analysis. It is clear that CNA and H-component of geomagnetic field variation correlate well for both the events. However the extent of CNA depends on the strength of the magnetospheric convection electric field and the duration of southward IMF Bz before the substorm onset. Nevertheless, a proper statistical study may explore the possible empirical relationship between convection electric field and CNA at a sub-auroral station such as Maitri.

Additionally, a day side CNA event which occur during 06 April, 2011 is also shown. Detail study of these type of CNA events were done in the chapter 4 and 5. LT distribution of CNA at Maitri was found to be significant. Most of the CNA occurrences were seen at the dawn hours. Least occurrences were seen at dusk sector, however their production is still an interesting topic.
Chapter 3

Substorm related CNA at Maitri

3.1 Introduction

The space weather events such as geomagnetic storm and magnetospheric substorm have been explained in the introduction part. This chapter precisely deals with the substorm related particle precipitations and subsequent cosmic noise absorption at Maitri, Antarctica. It is interesting to see the effect of substorm over Maitri being a sub-auroral location.

The very basic definition of substorm tells that it is a transient process initiated on the nightside of the earth in which a significant amount of energy derived from the solar wind-magnetosphere interaction is deposited in the auroral ionosphere and in the magnetosphere [Akasofu, 1964]. The disturbance created in the auroral ionosphere by precipitation of energetic particles during different processes has been of immense interest for the polar researchers [e.g., Newell and Meng, 1992; Burns et al. 1990; Meredith et al., 2011; Wing et al., 2013, etc.]. Magnetospheric substorms are also known to populate night-side inner magnetosphere and auroral ionosphere with electrons and ions of wide energy ranges [Birn et al, 1997; Wing et al., 2013]. Effects of enhanced population of energetic particles have been extensively studied using ground and satellite based observations [e.g., Arnoldy, 1974; Sotirelis et al., 2013 and references therein].
CHAPTER 3. Substorm related CNA in response to Interplanetary conditions

The energies of softer electrons (energy $< 10keV$) precipitating to the auroral ionosphere are absorbed in the E and F regions of the ionosphere and create magnificent optical auroral emissions. Additionally, low energy electrons enhance the auroral currents (electrojets) that can be easily monitored through magnetometers. Electrons of harder energies ($> 20keV$) reach to the D region of the auroral ionosphere [Wilson and Stoker, 2002; Baker et al., 1982; Meredith et al., 2011]. Transient changes of harder electron densities in the lower ionosphere could additionally be monitored by Riometer (Relative Ionospheric Opacity meter). Incoming intergalactic cosmic radio waves to the Earth are absorbed to different degrees while passing through the ionosphere depending upon electron densities [Hargreaves, 1969]. Thus, cosmic noise absorption (CNA) provides an indirect method for diagnostics of the state of the ionosphere. Moreover, the total energy budget entered into the magnetosphere can be simultaneously monitored by PC-index and CNA, as it has been observed that CNA is unanimously dependent upon the geomagnetic activity level, which is characterized by PC-index [Alexander Frank-Kamenetesky and Oleg Troshichev, 2011]. Various types of CNAs are commonly observed, e.g., F-region absorption, sudden cosmic noise absorption (SCNA), polar cap absorption (PCA), Auroral Substorm Absorption (ASA), dayside absorption spike events, poleward progressing absorption (PPA), etc., it is often possible to distinguish different types of absorption events on the basis of their appearances in the recordings of absorption intensities combined with knowledge of latitude, local time and season during the observations (Stauning, 1996).

Magnetospheric substorms initiate near midnight [Akasofu, 1968; Singh et al., 2012], as a result of which associated CNA events are often observed in the midnight sector of the auroral region during different phases of auroral substorms [Hargreaves, 1974; Jussila et al., 2004]. Generally, night-time CNA events are produced due to the precipitation of energetic electrons along the field lines from the injection region. However occasionally substorm-associated CNA events are observed towards morning or even noon sectors due to eastward drift of electrons [Kavanagh et al., 2002; Birch et al., 2013].

Numerous studies on the substorm-associated CNAs have been carried out in the past using
wide as well as narrow beam riometers [Ranta et al., 1981; Nielsen, 1980; Kikuchi et al., 1990]. With further advancement in instrumentation, multi-narrow-beam imaging riometers [Detrick and Rosenberg, 1990; Browne et al., 1995] were utilized to study the dynamics of substorms and CNA signatures on a relatively smaller spatial scale [Kavanagh, 2002; Kellerman and Makarevich, 2011; Hargreaves et al., 1997].

It has been reported that CNAs exhibit distinct features during different phases of a substorm, e.g., reduction in CNA during the growth phase due to the stretching of field lines and enhancement preceding substorm onset by a few minutes due to the dipolarization [Kellerman and Makarevich, 2011]. Dispersionless plasma injections into the inner magnetosphere are typical feature of a substorm onset [e.g., Birn et al, 1997]. CNA observed by a suitably located riometer has been demonstrated to be an effective tool for ground-based identification of dispersionless electron injections [Spanswick et al., 2007].

Electromagnetic and plasma properties in the near-Earth environment are closely related to changes in the solar wind parameters, e.g., southward orientation of the interplanetary magnetic field (IMF Bz) drive storms and substorms [Kullen and Karlsson, 2004; Gonzalez and Tsurutani, 1987], high speed solar wind streams generate HILDCAA events [Tsurutani and Gonzalez, 1987], pressure pulse compresses the magnetosphere and induce auroras [Liou et al., 2007], etc. CNA variations in response to the changes in the interplanetary conditions have been extensively examined [Meredith, et al., 2011; Korotova et al., 1997; Behera et al., 2014].

In this chapter, we have examined substorm-associated CNA absorptions observed at an Indian Antarctic station Maitri (MLAT $62^\circ$ S) in relation to the interplanetary conditions. Our station being located towards the equatorward boundary of the auroral oval (Hanchinal et al, 1996), occurrences of substorm associated typical signatures of magnetic variations and CNAs are relatively less frequent in comparison to those identified by AL negative bays.
CHAPTER 3. Substorm related CNA in response to Interplanetary conditions

3.2 Data sets and event selection

This study predominantly relied upon the data from 38.2 MHz (4 x 4 system) imaging Riometer installed at Indian Antarctic station, Maitri (Geographic coordinates: 70.75° S, 11.73° E; CGM coordinates: 62.59° S, 53.59° E; L=5; MLT= UT−1) during the austral summer 2009-2010. Further details on the riometer were already described in the chapter 2. In the present study, riometer and digital fluxgate magnetometer (DFM) data from Maitri have been used for the period November 2010 to October 2011 when both instruments were simultaneously operational. Location of Maitri is such that it comes under the influence of Sq currents during geomagnetic quiet conditions (Vichare et al., 2012) whereas during disturbed conditions auroral electrojets determine geomagnetic field variations at Maitri (Arun et al., 2005).

For identification of substorm events, we used the conventional AL index available from the webpage of WDC, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/aeasy/index.html). During the local night time at Maitri (2300-0500 MLT), AL, H-component variations at Maitri (MAI-H) and absorption data were visually scanned over the selected interval for selection of events. Maitri being in the southern hemisphere (in opposite hemisphere of AL stations) and near equatorward boundary of the auroral oval, AL negative bays are not always evident or comparable with MAI-H. Only those events were considered as substorm absorptions events for which sharp AL negative bay attained values ≤ −150 nT followed by concurrent westward electrojet signature (MAI-H ≤ −70 nT) over Maitri and CNA ≥ 0.2 dB. We ignored cases when there were significant (more than 15 minutes) delays between the onsets of MAI-H depression and CNA absorption.

We identified 31 clear substorm absorption events at Maitri over the selected one year duration. In order to examine the selected events in relation to interplanetary conditions, we used IMF and solar wind data obtained from OMNIWeb (http://omniweb.gsfc.nasa.gov/form/omni_in.html). OMNIWeb data are time shifted to the bowshock nose considering the travel time of solar wind from the location of observation [e.g., Weimer and King, 2008].
CHAPTER 3. Substorm related CNA in response to Interplanetary conditions

3.3 Observations

In this section firstly we have presented two typical CNA events associated with isolated substorms and one typical event associated with storm-time substorm to bring out the characteristic differences between these two types of CNA events. The description of these events is followed by a subsection dealing with the effect of interplanetary conditions on CNA considering all the 31 events of one year selected as per the criteria mentioned in section 3.2.

3.3.1 Event of 20 April 2011

A clear absorption event at Maitri was observed in association with an isolated substorm during 0300-0600 UT (0200-0500 MLT for Maitri). IMF Bz and Vsw taken from OMNIWeb is shown in the top two panels of Fig. ???. Occurrence of the substorm and its clear signatures in magnetometer and riometer data are evident as shown in the lower panels. Onset of sudden drop in AL leading to a negative bay started around 0410 UT, which appears to coincide with southward turning of IMF Bz. Vsw was steady (∼450 km/s) during the event. It may be noted that the AL negative bay lasts longer than the MAI-H depression or CNA enhancement. Moreover, Max |AL| (∼700 nT) is higher than Max |H| (∼400 nT) for the event that could either be due to difference in the location of Maitri with respect to substorm onset region or due to the hemispherical asymmetry. Intensity of CNA maximized to about 1.0 dB during the substorm. SYM-H pattern (> -35 nT) suggests that the substorm event occurred during a weak storm.

The last two panels in Fig. ?? represent latitudinal and longitudinal extent of the absorption for the event of 20 April 2011. Riometer observations show that absorption which in turn indicates particle precipitation maximizes around 62° CGM latitude and the longitudinal extent was over the complete field of view of the Maitri riometer. However the maximum CNA was observed around 55° CGM Longitude.
CHAPTER 3. Substorm related CNA in response to Interplanetary conditions

Figure 3.1: CNA event at Maitri during an isolated substorm on 20 April 2011. IMF Bz and Vsw are shown in the top two panels. Next, SYM-H is shown (third panel). In response to the AL negative bay (fourth panel), westward electrojet and CNA were clearly observed (fifth and sixth panel). Last two panels show latitude and longitude extent of the absorption.
3.3.2 Event of 9 August 2011

A substorm leading to westward electrojet and CNA absorption signatures at Maitri started around 0450 UT. IMF Bz and Vsw for the event have been shown in the top two panels of Fig. 3. Substorm appears to have initiated with reduction in IMF Bz, whereas Vsw remained steady. The max $|\text{AL}|$ was 600 nT for the event. Maitri was located in dawn hours during the substorm. It can be seen that the westward auroral electrojet extended to Maitri about an hour later from the onset of substorm. Variation in CNA clearly follows MAI-H variation. During the substorm event SYM-H dropped up to -25 nT, thereby suggesting that the event occurred during a very weak storm.

As shown in the bottom two panels for Fig. 4, precipitation of energetic electrons leading to CNA was mainly localized equatorward of Maitri station. Moreover, CNA was more intense in east longitudes during the event.

3.3.3 Event of 29 May 2011

A very intense storm-time substorm was initiated around 0500 UT, i.e., 0400 MLT for Maitri. The Dst index was -66 nT for the event. AL negative bay started when IMF Bz was southward and Vsw was quite high (650 km/s) for the event (Fig. 5). In a way similar to events discussed above, MAI-H or CNA variations lasted for shorter interval in comparison to AL variation. For this intense substorm event (Max $|\text{AL}|$ 1000 nT), Max $|\text{H}|$ reached to about 800 nT and Max (CNA) exceeded 2 dB at Maitri. Unlike the above two events, SYM-H value relatively reduced more and has gone down to -64 nT during this event.

Several bursts of absorption covering almost the field of view of Maitri imaging riometer system were observed during the substorm as shown in the bottom two panels of Fig. 6.
Figure 3.2: CNA event at Maitri during another isolated substorm on 9 August 2011. The parameters were plotted same as Fig ???. During this event, the substorm activity was moderate and less production of CNA at Maitri compared to the event on 20 April 2011.
Figure 3.3: CNA event at Maitri for a storm-time substorm on 29 May 2011. Intensity and region of CNA absorption are far greater than those for isolated substorms shown in Figs.?? and ??.
3.4 Statistics of substorm related CNA events

3.4.1 MLT dependence of the events

Fig 3.4 shows the distribution of 31 events during magnetic local night hours. Events are mostly confined to post-midnight and early dawn hours and this may be attributed to substorms primarily occurring around magnetic mid-night hours and the location of Maitri. We additionally examined SYM-H index during the selected events. It was observed that 26 absorption events occurred during moderate to weak storms (SYM-H $<-30$ nT), whereas only 5 events were not related to storm (SYM-H $>-30$ nT).

Figure 3.4: MLT distribution of onset of westward electrojet and CNA events for selected events at Maitri, Antarctica. Occurrence peaks around pre-midnight and early dawn hours.
CHAPTER 3. Substorm related CNA in response to Interplanetary conditions

3.4.2 Substorm onset, westward electrojet onset and CNA onset

For the selected events, correlations among the intensities of the global AL index, MAI-H and CNA over Maitri have been shown in Fig. ??a. Magnitudes of maximum depressions in the AL index (Max $|AL|$) and MAI-H (Max $|H|$), and corresponding maximum enhancement in CNA (Max (CNA)) were estimated for each event. The scatter plots for Max $|AL|$ vs Max $|H|$ (correlation coefficient, $r = 0.86$), Max $|H|$ vs Max (CNA) ($r = 0.79$) and Max $|AL|$ vs Max (CNA) ($r = 0.67$) have been shown in Fig. ??a. This ensures that the selected absorption events are associated with substorms.

Linear relationship between the Max $|AL|$ and Max $|H|$ clearly suggests that during the selected events the maximum intensity of the westward auroral electrojet observed over Maitri during night time varies with substorms intensity observed by the global AL index in the northern hemisphere (Fig. ??a). For the selected events, intensity of CNA at Maitri also
CHAPTER 3. Substorm related CNA in response to Interplanetary conditions

changes with varying intensities of the substorms or westward electrojet intensification at Maitri as shown in Figs. ?? b and ?? c. However, intensity of the absorption is better correlated with MAI-H intensity, which is obvious as both the observations are from the same location. Here, note that we have selected those absorption events which are accompanied by substorms; figure ?? c further demonstrates that being associated with substorms, how CNA varies with AL.

In the following section, we investigate CNA events observed at Maitri in relation to interplanetary conditions.

3.4.3 Effect of interplanetary conditions on CNAs

Geomagnetic activity is mainly controlled by the southward IMF Bz, Vsw and dawn-dusk interplanetary electric field, Ey (= - Vsw x Bz). In this section we examine variations of Max |AL|, Max |H| and Max (CNA) for all the selected events in relation to Bz, Vsw and Ey. In a way similar to the maximum values of |AL|, |MAI-H| and CNA for each event, we calculated the highest magnitudes of southward IMF Bz (Max |IMF Bz|), duskward IMF Ey (Max Ey) and Vsw (Max Vsw). Scatter plots of Max |Vsw| vs Max (CNA) (r = 0.50), Max |Bz| vs Max (CNA) (r = 0.75) and Max Ey vs Max (CNA) (r = 0.85) are shown in Fig. ?? . Poor correlation between the maximum Vsw and CNA intensity at Maitri suggests that solar wind speed alone does not effectively determine the level of particles precipitation over Maitri (Fig. ??a). However, for higher magnitude of southward IMF Bz during the substorm, precipitation of electrons leading to increased CNA (Fig. ??b). Intensity of the absorption is highly correlated with the maximum duskward IMF Ey (Fig. ??c). It clearly suggests that the duskward oriented interplanetary electric field was the most important controlling factor for CNAs observed at Maitri.

Moreover, for all the selected events IMF Bz was southward in the vicinity of onset of AL negative bay. The Max |IMF Bz| varied between 2 to 22 nT. Although substorm-associated
Figure 3.6: Scatter plot of the maximum intensities of (a) $V_{sw}$ vs CNA (correlation coefficient, $r = 0.5$), (b) southward IMF $B_z$ vs CNA ($r = 0.75$) and (c) duskward IEF $E_y$ vs CNA ($r = 0.85$) for selected events. CNA intensity at Maitri has strong dependence on IEF $E_y$. 
CHAPTER 3. Substorm related CNA in response to Interplanetary conditions

CNA events occurred during a wide range of southward IMF Bz conditions, figure (??b) clearly shows most of the events were observed when IMF Bz was weakly southward. For the selected events, the Max |Vsw| varied from about 300 to 725 km/s (Fig.??a). It is observed that the occurrence of absorption events at Maitri, however, do not have strong dependence on the solar wind speed.

3.5 Results and discussion

Precipitation of energetic electrons into the auroral ionosphere usually affect different regions depending upon their energies, e.g., westward auroral electrojet is driven by low energy electrons precipitated in the E-region, whereas higher energy electrons lead to cosmic radio noise absorption in the D-region [Wilson and Stoker, 2002; Baker et al., 1982]. During magnetospheric substorms (as identified by the AL index), we selected 31 associated events at Maitri based on concurrent response in the magnetometer and riometer data. Substorm-associated CNA events were mainly localized near local midnight, which is consistent with earlier observations [e.g., Kellerman and Makarevich, 2011].

The maximum intensities of MAI-H and CNA at Maitri were well correlated with the intensity of AL index (Fig.?? ). However, we observed that the MAI-H negative bays were short-lived and corresponding maximum intensities (max |H|) were consistently lower than those for AL negative bays as shown in Figs. ?? to ?? . AL index being the lower envelop of H component disturbance from about 10-12 stations (Davis and Sugiura, 1966), negative bay could last longer due to contributions from other stations where westward electrojet maximizes. Moreover, hemispherical asymmetry in the substorm signatures [Weygand and Zesta, 2008; Singh et al., 2012] and the location of Maitri station (equatorward of auroral oval in the southern hemisphere) could be other reasons for the difference between AL and MAI-H signatures.

High correlations of Max |H| vs Max (CNA) (Fig.?? b), and MAI-H vs CNA for individual substorm events (see Figs.?? – ?? ) clearly suggest that softer and harder energy electrons, respectively affecting upper and lower regions of the ionosphere, simultaneously precipitate
to the auroral ionosphere during sustorms.

Isolated and storm-time substorms mainly differ by the magnitude and extent [Feldstein et al., 2006; Partamies et al., 2013]. It is evident from Figs.?? and ?? that for isolated substorm events, absorptions over Maitri were quite localized in latitude (± 2 degrees), but fairly wide in longitude (about 5 degrees). For storm-time substorm absorption was much intense and covers the entire field of view of the riometer (Fig.??).

At Maitri station, most of the substorm-associated CNA events (26 out of 31) were observed during moderate to weak magnetic storms and predominantly under southward IMF Bz conditions. Studies based on the simultaneous particle flux data from NOAA POES satellite and Imaging riometer data from Kilpisjarvi (69.050 N, 20.790 E, geographic coordinates) suggest that the intensity and local time of the particle precipitation and CNA change dramatically during high speed streams (HSS) of the solar wind (Meredith et al., 2011; Kavanagh et al., 2012). Although our study does not address HSS, we observed that the occurrence frequency of CNA events is independent of the speed of solar wind (Fig.?? a). Nevertheless, there is an indication of increased CNA intensity with increasing solar wind speed. Intensity of southward IMF Bz during the substorms clearly increased the level of absorption at Maitri (Fig 6b). It is consistent with the finding of Kavanagh et al. (2004; 2012) that negative IMF Bz produces higher CNA across all L-shells and MLT.

across all L-shells and MLT. The dawn-dusk component of the interplanetary electric field (Ey), which depends on solar wind speed and IMF Bz, is known to be extremely important for driving geomagnetic activity (e.g., Huang et al., 2005; Chakrabarty et al., 2008). Maximum intensity of absorption at Maitri (Max (CNA)) almost linearly increased with increasing duskward IEF Ey intensity as shown in Fig.?? c.

3.6 concluding remarks

Our analysis of about 1 year magnetometer and riometer data of Maitri station, Antarctica in relation to magnetic substorms and interplanetary conditions suggests that:
1. Onsets of the westward electrojet and cosmic noise absorption at the station were centered around local midnight. Intensity of the electrojet and CNA over Maitri were almost linearly related to the intensity of (northern hemispheric) AL index.

2. At Maitri, westward electrojet and cosmic noise absorption were mainly observed during storm-time substorms possibly due to the location of the station near equatorward boundary of the auroral oval.

3. A clear distinction in the intensity and extent of the absorption region was observed for isolated substorm and storm-time substorm cases. Usually storm-time substorm absorption events were far more intense and covered wide latitude and longitude regions.

4. Magnitudes of the southward IMF Bz or duskward IEF Ey were linearly related to intensity of CNA at Maitri. Moreover, increasing solar wind speed and IMF Bz appear to cause enhancement in the precipitation of harder electrons leading to enhanced CNA.
Chapter 4

Day side CNA (DCNA) and wave-particle interaction

4.1 Introduction

This chapter deals with the rare kind of CNA event that occurred during the day time. These kind of CNA are the results of a different type of inner magnetospheric phenomena which involves wave-particle interactions. Again, this work has focused at Maitri as the prime location of study. However, a set of different riometer stations were taken to validate the observations. The process of deposition is either in the open field line region at the day side of magnetosphere or, in the closed field line region in the night side [Newell and Meng, 1992]. The night side precipitations is mainly due to high energetic electrons in the energy range of (>20 Kev) inside the auroral region [e.g. Hargreaves, 2007]. Softer electrons (<10 Kev) are responsible for auroral display and in some part for intensification of auroral electrojet in ionospheric E and F regions. Semeter et al. [2001] have used new multispectral imager and associated multispectral analysis to understand the connection between the auroral morphology and the auroral optical spectrum in the same region of ionosphere. However, harder electrons such
as 30 KeV to few MeV can penetrate deeper in to the ionosphere and subsequently affect the composition of the middle atmosphere [Codrescu et al., 1997]. The use of wide beam riometer for the particle precipitation could not provide the spatial information of the CNA pattern and later was replaced by advanced arrays of riometers forming different beams in 1990 and are called imaging Riometer [Detrick and Rosenberg, 1990]. The basic technique of imaging RIometer is to receive the radio noises from the interstellar region at a particular radio frequency [Honary et al., 2011]. Indian Institute of Geomagnetism operates an Imaging Riometer of 4X4 antenna system at Maitri, whose operating frequency is 38.2 MHz. CNA is often measured in decibel and it can be calculated by simply following equation,

Various types of CNA are attributed to different solar-terrestrial phenomena such as storm sudden commencement related CNA, X-ray flare generated CNA, substorm related CNA etc [Stunning et al., 1996]. Substorm related CNA during midnight hours are very frequent and well studied [Ranta et al., 1999; Lopez and Lui, 1990; Jun Liang et. al., 2007]. However, these CNAs can sometimes be observed in the extended range of local time depending upon the latitudinal and longitudinal expansion of auroral oval, which is a consequence of the ionospheric plasma convection due to injection of energetic particles from the tail during midnight sector [Ansari, 1964]. Many researchers have discussed about the morning side CNA as well as pre-noon hour CNAs. However, very few cases of dayside CNA event from sub-auroral locations and no DCNA event from Maitri have been reported so far. Additionally, very little is known about its possible cause. Researchers have suggested that the higher energy electrons (> 20 KeV) are responsible for high latitude day side cosmic noise absorption [Matthews et al., 1998; Newell and Meng, 1992; Ostgaard et al., 1999b]. It is shown that the electrons associated with central plasma sheet, being injected in the night side of the magnetotail, mostly in midnight hours and further fall into loss cone during gradient-curvature drift in the inner magnetosphere. This kind of precipitation at high latitude is possible due to cyclotron resonance between the electrons in the Earths radiation belt and chorus waves causing pitch angle scattering into the loss cone during different geomagnetic activity [Ding et al., 2013; Su et al., 2014; Xiao et al., 2009, 2010, 2014]. Presence of Pc5 pulsation and whistler mode VLF
emission during the morning side precipitation and further production of CNA are well known phenomena at high latitude (L=5.1-5.5) [Manninen et al., 2010]. These whistler-mode chorus is observed in the frequency range 0.5-2.5 KHz outside the plasma pause and is one of the driver of energetic electron precipitation especially in the dawn sector [e.g., Pasmanik and Trakhtengerts, 1999; Bortnik and Thorne, 2007; Gokowski and Inan, 2008].

CNA may also differ in many aspects such as time of occurrences, magnetic signatures, and intensity. For example, the auroral substorms are often associated with the westward electrojet and they are almost concurrent. Generally, substorms occur in the pre-midnight sector [Frey and Mende, 2006] and populate the inner magnetosphere due to field aligned propagation of energetic particles immediately after the reconnection process starts [Spanswick et al., 2007; Liang et al., 2007]. Hence, the westward electrojet intensification and CNA onset is almost instantaneous with respect to auroral substorms and has been observed at Maitri, Antarctica [Jayanta et al., 2014]. Hence, there must be a significant westward signature if a CNA enhancement is observed in any location inside the auroral oval. However, in the current study, the CNA event that falls in the day-side, has no simultaneous signatures of westward electrojet at the same site of observation in Maitri.

Interplanetary parameters are key to understand the cosmic noise absorption pattern, notably the effect of IMF, Solar wind pressure and interplanetary Electric field [Sandholt and Newall, 1996; kavanagh et al., 2004, Jayanta et al., 2014]. Changes in dynamic pressure due to solar wind velocity could lead to the enhancement in precipitation. It is statistically shown that the average CNA becomes larger with increasing level of solar wind velocity [Kavanagh et al., 2004]. Basically, solar wind velocity has to be the driving cause for the geomagnetic activities and a proxy to total energy input to the magnetosphere. Characteristics of southward component of interplanetary magnetic field (IMF Bz) is crucial for understanding different types of CNA observed at high latitude. For example, northward turning of IMF Bz after being southward for a certain duration of time would give rise to onset of substorms at high latitude. The duration and the extent of IMF Bz, decide the level of substorm activity. Moreover, during high speed solar wind events, it is shown that a negative IMF Bz has produced higher CNA
CHAPTER 4. Characteristics of DCNA at Maitri

across all L-shells and MLT, up to 100% higher than positive IMF Bz (Kavanagh et al., 2012). However, northward IMF can also produce CNA, but at the poleward edge of the cusp with auroral signatures [Sandholt et al., 1996; ieroset et al., 1997; Sandholt et al., 2000]. Nevertheless, the longer sustainability of larger interplanetary electric fields is more appropriate to correlate with the level of CNA production at high latitude due to substorm activity [Behera et al., 2015].

In this chapter, initially, we have defined the characteristics of a day side CNA event and thereafter a comparison is made between two different days of 02 April 2011 and 14 July 2011. Though the substorm occurrences took place on both these days, the day side CNA occurred only on one of the days. The study location is Maitri, Antarctica (L=5, geog. 70.75° S, 11.75° E, CGM 62.45° S, 55.45° E). The above exercise was done to identify the necessary and sufficient condition for the occurrence of the day side CNA event. The comparative study has been carried out in the light of ground magnetic signatures, Riometer signatures, interplanetary conditions, GOES satellites observation of particle fluxes in different energy bands (40, 75, 150, 275 and 475 KeV) and associated pulsations. Additionally, successive delays of the onset of CNA at longitudinally distributed stations inside the auroral oval have also been examined. Temporal delay between the onset of the substorm and onset of CNA at Maitri has been attributed to the azimuthally gradient drift of energetic electrons. We use this delay time in the gradient-curvature drift equation (Baharell et. al, 2015) to get an order of energy estimate of the electron fluxes. The abrupt enhancements in electron fluxes in certain energy bands as observed from different GOES satellites could result into the occurrences of day side CNA event as observed on 02 April, 2011.

4.2 Data sets

Again the data sets used for the study includes imaging Riometer data from (Maitri) The antenna consists of 16-elements dipole phased array which provides 16 imaging beams and a
CHAPTER 4. Characteristics of DCNA at Maitri

A single wide beam over a 200 X 200 km field-of-view. The horizontal beam width is approximately 20 km at an approximate height of 90 km (D-region) near the zenith and all the beams data were sampled at one second. Moreover, this riometer has both wide beam and narrow beam (Image beam) facility; the wide beam provides the enhanced CNA information quantitatively where as Image beam provides the spatial evolution of the CNA patterns.

Additionally, Indian Institute of geomagnetism also runs a Digital Fluxgate Magnetometer (DFM) at Maitri since 2003. The sampling rate of data acquisition of the DFM is one second with 1 nT resolution. The Imaging Riometer and DFM are operated together at Maitri to study the substorm related particle precipitation characteristics and the dynamics of auroral electrojet current systems. Bharati (CGM 74.4° S, 97.2° E) is another newly commissioned Indian Antarctic station, where characteristics of poleward substorms studies are going on. [Singh et. al, 2012].

To identify the substorm onset time and its strength, we have used AL- index and Wp-index from the WDC, Kyoto site. Recently, Wp (Wave and Planetary) index has been introduced by Nose et al. [2014] as a new and more authentic indicator of substorm onsets [Thomas et. al., 2015]. This index shows the wave power of the Pi2 pulsation at low latitude, which was derived from geomagnetic data from 11 low latitude stations. Singh et. al. [2012] has shown the importance of fixing criteria on AE/AL index enhancement/depression to identify a substorm. For identifying substorm onset, we impose the condition on AL that there should a transient depression of more than 150 nT within a time span of 2 minutes. SYM-H and DST-index data have been used as a proxy for the ring current enhancement during the course of the observed events. For interplanetary parameters such as interplanetary magnetic fields, solar wind velocity, interplanetary electric field etc., data have been taken from the OMNIWEB data centre (http : //omniweb.gsfc.nasa.gov/form/omnin.html). The in-situ measurements of energetic electron flux injections have been obtained from GOES-13 satellite.

The Geostationary Operational Environmental Satellite (GOES) consists of Energetic particle sensor and magnetometers as part of Environment monitoring instruments. These energetic particle fluxes are given as one minutes/five-minute average values and the vector magnetic
field data is given by one minutes average values. Flux values for integral electron channels $(E > 0.8 \text{ MeV}, E > 2.0 \text{ MeV})$ and electron fluxes 40-475 KeV data can be collected from the CDAWEB website of NASA (http://cdaweb.gsfc.nasa.gov/cgi-bin/eval1.cgi). In the current study, we have used GOES-13 and GOES-15 EPS (Energetic Particle Sensor) MagED (Magnetospheric Electron Detector) 1 minute electron fluxes data in the energy band of 40-475 keV. These data are mainly provided by NOAA NGDC and SWPC (sem.goes@noaa.gov).

In order to study the global Pc5 oscillation characteristics, magnetic field variations as recorded by DFM were used from some of the INTERMAGNET stations. Geomagnetic component variation data with 1 minute resolutions were taken in the IAGA-2002 format from the INTERMAGNET data website (http://www.intermagnet.org/data−donnee/data−eng.php). The stations were taken arbitrarily to see the global Pc5 oscillations during the event days. Geographic and geomagnetic co-ordinates of the INTERMAGNET stations are given in table-1. For the current study, riometer data were used from some of the stations such as DAWS, HSIM, GILL, RABB of NORSTAR (NORthern Solar Terrestrial ARray) riometer chain (http://aurora.phys.ucalgary.ca/norstar/index.html) and MCQ station of Australian Riometer chain. Co-ordinates for these stations are provided in table -2.

4.3 Observations

4.3.1 A day side absorption event with interplanetary conditions

On 02 April, 2011 enhancement in the CNA occurred twice at Maitri at $\sim 0640 \text{ UT}$ and $\sim 1144 \text{ UT}$. To identify CNA onset, we impose the condition that there should be an enhancement of more than 0.3 dB within 2 minutes. This criterion is an extension of the criterion (CNA $> 0.2$) given in Behera et al., [2015] to identify a CNA event at Maitri. The time constraint was added in order to identify the CNA event at different stations to examine CNA characteristics at longitudinally distributed stations inside the auroral oval during the substorm on 02 April, 2011.
(mentioned in discussion section, figure-9). Just by looking at the transient enhancement, it was difficult and ambiguous. Occurrence durations of these two events were approximately 01 hr 12 minutes and 01 hrs 54 minutes respectively. Associated geomagnetic activities were completely different for these CNA events. In Figure ??, the top two panels depict AL-index and Wp-index which are essentially indicator of the substorm onset. The next panel represents the horizontal component of geomagnetic field at Maitri. The fourth panel from the top represents wide beam CNA data. The calculation of CNA was done using equation-1. The quiet day curve (QDC) for cosmic noise signal have been computed by following strict criteria [Behera et al., 2014]. The second last panel represents sym-H and the bottom most panel shows the keogram of the imaging Riometer which gives the image plot of cosmic noise enhancement across the field of view of imaging Riometer at Matiri.
Figure 4.1: Ground signatures of CNA events on 02 April 2011 at Maitri. The two upper most panels show AL-index and Wp-index, respectively. Third and fourth panels represent the variation in the horizontal component of geomagnetic field and wide beam CNA at Maitri, respectively. Sym-H has been plotted in the second bottom most panel and the last panel shows the keogram of the imaging Riometer. The dashed line indicates the onset of auroral substorm absorption events whereas as first solid line represent the onset of the second substorm and second solid line shows the onset of CNA at Maitri. The delay between the onset of substorm and CNA onset at Maitri is a typical characteristics of DCNA.

Close observation of AL-index reveals onset of two substorms that have occurred at 0640 UT and 1120 UT. For both events the AL-index has gone down to \( \sim -700 \) nT and \( \sim -750 \) nT, respectively. Interestingly, we have observed CNA enhancement in the riometer data related
to these substorm occurrences. However, the onset time for both the CNA didn’t coincide with the substorm occurrences. The first event for which substorm and CNA onset coincides is well understood and can be termed as auroral substorm absorption events where charged particles precipitated in the auroral oval during substorm process [Jayanta et al., 2015]. Additionally, during auroral substorm absorption events, occurrence of westward electrojet is commonly observed at the site of the observation. The later CNA event also seems to be related to substorm activity. However, a clear delay of 24 minutes between the onset of substorm and onset of CNA is observed. There is no indication of the intensification of westward electrojet in the H-component variation. The forth panel represents the image plot of the intensification of the CNA and its areal coverage. It can be clearly observed that both the CNA enhancements are very localized but the intensity of the later event is high compared to earlier event. The delay (in onset) for the second event is clearly visible in this image also. Interestingly, SYM-H (< -30 nT) indicates the presence of a moderate geomagnetic storm and enhancement of ring current during 02 April 2011.
Figure 4.2: Interplanetary conditions during 02 April 2011. Two upper most panel show IMF Bz and solar wind velocity Vsw. The next two bottom panels represent solar wind pressure Psw and IEF Ey. The solid lines indicate the time of onset of the substorms.

In Figure ??, solar wind velocity (Vsw), solar wind pressure (Psw), interplanetary parameters such as IMF Bz, IMF By, and Interplanetary Electric field components (IEF Ey and IEF Ez) have been plotted respectively from top to bottom panel. It is observed that IMF was southward for a while before the onset of the substorm in the events. However, IMF Bz remained south-ward for a longer time \( \sim 02 \) hrs before the onset of the second event as compared to the
first one. Solar wind velocity was initially moderate $\sim 400$ km/s and picked up to 600 km/s later. The solar wind pressure indicates no drastic change during the course of the events. It was steady with a value between 1.5-2 nPa. Interplanetary electric field (IEF= $-V_{sw} \times B_z$) depends quantitatively upon solar wind velocity and IMF $B_z$ and its direction depends upon the IMF $B_z$ orientation. The direction of IEF $E_y$ is eastward or, westward depends upon whether IMF $B_z$ is southward or, northward respectively. IMF $B_y$ was consistently westward during both the substorms with eastward turning on couple of occasions such as $\sim 0840$ and $\sim 1110$ UT. Corresponding to $B_y$ orientation IEF $E_z$ was northward with couple of southward turnings. Average Strength of IEF $E_z$ was less than 2.5 mv/m. during both the substorm. In this work, we are concentrating on DCNA event i.e the event that occurred in the later time (1100-1400 UT) during 02 April, 2011. Prior to the event, IEF was eastward for more than 1 hr and turned westward before the onset of the substorm. The value of IEF was approximately 5 mV/m, which is larger than that during the auroral substorm CNA event.

Generally, a substorm is accompanied by westward electrojet which is observed as a significant depression in the H-component variation in the geomagnetic field inside the auroral oval. At Maitri, signatures of westward electrojet have been reported during substorm onsets [Jayanta et al., 2015]. However, the onset of westward electrojet, sometimes, matches with the onset of substorm or may get delayed depending upon the location of study. On 02 April 2011, though two CNA events were observed, westward electrojet is observed only for the first event, where as we dont observe any westward electrojet for the second event of CNA during the later substorm occurrence despite the fact that the later susbtorm was relatively intense. Also, for the second event clear delay between the susbtorm onset and CNA onset is quite evident. The detail discussion on the delay has been presented in section ???.
4.3.2 A day side no-absorption event with similar Interplanetary conditions

In contrast to the event of 02 April 2011, a substorm occurred on July 14, 2011 during 1000-1130 UT is presented here. Figure ??, similar to Figure??, represents the two topmost panel showing AL-index and WP-index. Next two panels represent the variation in H-component and wide beam CNA at Maitri, respectively. The second last panel depicts Sym-H and the bottom most panel shows the keogram of imaging Rioemter.

The substorm has occurred at 1010 UT on 14 July, 2011. AL-index showed a strong depression of 800 nT. Wp-index, during this time was pronounced and certainly confirmed the occurrence of substorm. However, during this substorm, Maitri did not show any production of CNA or westward electrojet. Moreover, SYM-H indicates absence of any ring current enhancement.

Figure ?? represents the interplanetary parameters during the event of 14 July 2011. Though IMF Bz was southward before and after the onset of the substorm, the level of IMF Bz was less (∼ -2nT) compared to the event of 02 April 2011. It was only ∼ -2 nT. Solar wind velocity was quite steady (∼ 500 km/s) Though it is above the average solar wind velocity, no abrupt change or enhancement was observed during the substorm. Same was the case for solar wind pressure. IMF By was initially eastward then turned westward during the onset of the substorm. We notice that the interplanetary electric fields (IEF Ey and IEF Ez) parameters are consistently low (0-1 mv/m.) during the substorm.

4.3.3 GOES-13 observation during both the event

Despite the fact that both days had fair substorm activity, enhancement in the CNA during daytime occurred only on 02 April 2011. In order to identify the possible cause of the differences observed for the studied days, we examined the particle data from GOES-13 and GOES
Figure 4.3: Same as figure-1, but for 14 July, 2011 substorm event
Figure 4.4: Same as Figure-2 but on 14 July, 2011
-15. Figure 22 represents the fluxes of electrons of different energy levels for the days of 02 April 2011 and 14 July 2011. Both the panels represent the fluxes of non-relativistic electrons within the range of 40-475 Kev. The left panel corresponds to the event of 02 April, 2011 and the right panel corresponds to 14 July, 2011. The two black solid lines represents the time of onset of the substorms at 1120 UT for 02 April 2011 and 1010 UT for 14 July 2011. During the substorm occurrence at 1120 UT on 02 April 2011, Maitri was at 1020 MLT, GOES 13 was at 06 MLT and GOES 15 was at 05 MLT. For the substorm event of 14 July 2011 which occurred at 1010 UT, Maitri was at 0910 MLT, GOES 13 was at 05 MLT and GOES 15 was at 04 MLT. Sudden enhancement is observed in all the electron fluxes during both the events. However, it can be seen that fluxes in the energy ranges of 150 KeV and 275 KeV have larger enhancements at the susbtorm onset time on 02 April 2011 compared to other day i.e. 14 July 2011.

Fluxes in the energy ranges of 45 and 75 shows approximately same order of enhancement during both the days. At the onset, the magnitudes of the 150 KeV and 275 KeV fluxes were $4 \times 10^3 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ and $6 \times 10^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ respectively, which later increased up to $7 \times 10^3 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ and $5 \times 10^3 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ respectively. Whereas, in case of 14 July 2011, magnitudes of similar energetic electrons were $7 \times 10^3 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ and $1 \times 10^3 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ respectively, which later increased up to $3 \times 10^4 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ and $3 \times 10^3 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ respectively. Hence, more precisely we can find that 16.5 times increment in the flux density of 150 Kev and 7.3 times in 275 Kev electrons during 02 April, 2011 where as only 3 times increment in density of 150 KeV and 2 times in 275 KeV electrons during 14 July, 2011. Fluxes enhancement in the energy range of 475 shows increment of only $100 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{KeV}^{-1}$ during the onset of 02 April, 2011 compared to 14 July, 2011, which is less significant in comparison while discussing the cases of 150 and 275 KeV energy bands.
Figure 4.5: 1 minutes resolution data of 40-475 KeV electron flux densities by GOES-13 for 02 April 2011 and 14 July, 2011. Solid bars both the panels indicate the onset of substorm for these days for example 1120 UT is the onset time of substorm on 02 April, 2011 and 1010 UT is the onset time of substorm on 14 July, 2011
Evolution of electron cloud observed by GOES 13 and 15 for DCNA

Here, we are examining the evolution of electron fluxes for 02 April, 2011 on which we observed DCNA event. Electron flux data during the substorm onset on 02 April, 2011 were available for two GOES satellites (GOES-13 and GOES-15) separated in MLT by 1 hr during the substorm onset. At the substorm onset, GOES-13 was located at 06 MLT and GOES-15 was located at 05 MLT. Hence, GOES-15 was closer to magnetic mid-night than GOES-13 and was likely to encounter with the electron clouds earlier than GOES-13.

Figure ?? shows the electron fluxes of 40-475 KeV range during the substorm period. Substorm onsets at $\sim 1120$ UT and we can clearly see the electron clouds encountered by both the GOES satellites. However, GOES-15 shows enhancements in the electron flux for all the energy ranges prior to these observed in GOES-13. A delay of $\sim 3$-7 minutes in peak enhancement of electron flux was observed between the two satellites. We have observed shorter delay times for higher energy electron flux drift and longer time delay associated with lesser energetic flux. For example, maximum time delay of $\sim 7$ min. is observed between the peak enhancement of electron flux in 40 KeV energy band as detected by GOES 13 and GOES 15. Electron Fluxes of energy 40 KeV and 75 KeV show gradual enhancement from the time of substorm onset and exhibit very slow recovery, thereby signifying moderate loss of electron fluxes in these energy bands. On the contrary, fluxes of energy 150 KeV and 275 Kev show delayed and sharp enhancements with steep recoveries indicating the loss of electrons for these energy bands. Hence, electrons in these energy bands are more likely to precipitate resulting in to the observed CNA. Enhancement in 475 KeV band is not so significant.

4.4 Global Pc5 (2-7 mHz) waves observed with DCNA

For decades, it has been proved theoretically as well as ground and satellite [Sinha et. al, 2005] observations that Pc5 pulsation has a great role in controlling the precipitation of charged
Figure 4.6: Electron cloud of energy bands 40-475 KeV encountered by GOES-13 and GOES-15 during the substorm on 02 April, 2011. At 1120 UT (Approximate onset time of substorm), GOES-13 was located at X= -0.101, Y= -6.508 and Z= 1.173 (RE, GSM) and GOES-15 was at X= -1.659, Y= -6.275 and Z= 1.6 (RE, GSM)
particles at high latitude [Kremser et al., 1981; Kleimenova et al., 1997, 2005]. Together with VLF chorus, ULF pulsations are typically observed at auroral latitudes in the morning sectors and have close relation with loss of particles either due to parallel accelerated electrons in field line resonance process [Nose, 1998] or, due to pitch angle scattering [Spanswich et al., 2005]. Hence, in order to examine the presence of global Pc5 pulsation, we have taken magnetometers data from the selected stations from INTERMAGNET. The location of the selected stations is given in the table.

In Figure, the H-component of the selected stations filtered at Pc5 pulsation range (2-7 mHz) for the duration of 1000-1400 UT on DCNA and no DCNA day have been plotted. The left figure is for 02 April 2011 and the right figure is for 14 July 2011. Note that the stations used here are from different MLT and latitudinal sectors. The presence of global Pc5 activity can be seen on both the days. Being in the auroral zone, the pulsation activity was strongest at CSY station on both days. OVATION model provides the auroral zone boundary, position and intensity of precipitation (http://sd-www.jhuapl.edu/Aurora/ovation/ovationdisplay.html). On 02 April 2011, OVATION plot for the auroral oval confirms (see figure) CSY station was located well within the auroral oval, where as rest of the stations mentioned in table 4.1 were far away from the auroral oval. Unfortunately, there is no plot available for 14 July 2011 during the substorm period (1000-1200 UT).
Near the onset of the substorm (marked by vertical lines) large amplitude pulsations are observed at almost all stations during both days. However, on 14th July, the amplitude of the pulsation activity reduced significantly after the recovery of the substorm (11 UT onwards), while on 2 April, fairly good amplitude pulsations were observed for longer duration.

DFM at Maitri collects geomagnetic data at 1 second sampling interval. The collected data are then filtered in Pc5 range (1-7 mHz). Dynamic spectra for both the days have been constructed and is shown in figure 8. The FFT was carried out using sliding window of 1024 points (~17 minutes) with an extra overlap of 50% points. In Figure ??, the dynamic spectra of both days clearly show the presence of pulsation activity in the Pc5 range during the substorm activity for each days. However, Pc5 pulsation activity is seen more pronounced during the day when DCNA was present compared to the day of no DCNA (14 July 2011). Figure ??(a) and ??(b) represent the dynamic spectra of raw H-component on 02 April 2011 and 14 July 2011 respectively. The time series of H then filtered in the Pc5 range (2-7 mHz) and have shown in figures ??(c) and ??(d) for 02 April, 2011 and 14 July, 2011 respectively. A clear trail of Pc5 oscillations during the event of 02 April, 2011 (which shows DCNA event) with peak to peak amplitude of 25 nT is seen, whereas the same for the event of 14 July, 2011 (not showing DCNA) is only 8 nT.

4.5 Discussion

For the first time, a comparative study has been made between the days of substorm occurrences with and without day side CNA at Maitri, Antarctica which can be useful to indentify the possible cause of day side absorption events. DCNA are not found to be associated with auroral westward electrojet, while night time CNAs are mainly accompanied with westward
Figure 4.7: Ovation plot for the auroal oval shows the location of CSY
Figure 4.8: Left figure is 2-7 mHz filtered H-component at selected stations for the interval 10-14 UT on 02 April 2011. Right figure shows the same but for 14 July 2011. The stations are arranged with decreasing order of latitudes. All stations are of different longitudes.
Figure 4.9: (a) and (b) show the dynamics spectra of raw H-component at Maitri location on 02 April, 2011 and 14 July, 2011 respectively. (c) and (d) represent the filtered H component in Pc5 pulsation range (1-7 mHz) on 02 April, 2011 and 14 July, 2011 respectively.
electrojets (Behera et al., 2015). Though both of events occurred during substorm activity, however, many a dissimilarities have been observed during these days in terms of interplanetary conditions, particle flux density and amplitude of Pc5 pulsations.

While studying the interplanetary parameters such as solar wind velocity, IMF Bz, dusk-ward Interplanetary electric field and solar wind pressure during the DCNA and no DCNA event days, it is clear that substorm occurred when IMF Bz was southward. However, we observe significant difference between the state and duration of southward IMF Bz during second substorm event of 02 April 2011 (1100-1300 UT) and the substorm event (1000-1200 UT) on 14 July 2011. On 02 April 2011, the southward IMF Bz decreased up to -6 nT (couple of times dipping below -6 nT) and it was consistently southward for ~ 2 hrs from 0900 UT onwards. The solar wind was high (~600 km/s). Consequently, the interplanetary electric field was consistently eastward for couple of hours (~5 mv/m.). Whereas, on 14 July 2011 the maximum southward IMF Bz was less than -2 nT and it was southward for less than one and a half hour, though the solar wind velocity during this time was above average (~500 km/s). The interplanetary electric field though eastward, was small (~1 mv/m). We believe that effect of IMF By and corresponding IEF Ez during the DCNA and no DCNA days will have very minor contribution to production of CNA. Basically, IMF By decides the longitudinal extent or, the azimuthal range of substorm westward electrojet (Arun T. et. al., 2009; Friis-Christensen and Wilhjelm, 1975). Polarity of By governs the dawn-dusk shift of 2-cell current system at high latitude. Rodger et al (1984) showed the local time shift of Harang discontinuity depending upon the polarity of IMF By. However, this study precisely examines the characteristics of CNA during day time at Maitri , where no signature of auroral electrojet is evident. The reason for DCNA is mainly the precipitation of large eastward drifted electrons flux which is mostly controlled by IMF Bz and IEF Ey.

GOES-13 observation is helpful in understanding the difference between the electron flux density involved in these two events. If we compare the time windows of the two events i.e.
1100 UT onwards for 02 April 2011 and 0900 UT onwards for 14 July 2011 wherein substorm have occurred, strong CNA is observed on first day while as the other day does not reflect any CNA. Electron flux data showed in Figures 5 for sub-relativistic energy range (40 KeV, 75 KeV, 150 KeV, 275 KeV and 475 KeV) shows clear differences in the flux densities. For both the days, enhancements in the electron flux in these above energy ranges are seen at the substorm onset. However, electron fluxes during the DCNA day (02 April, 2011) show increase by 16.5 times and 7.3 times in the energy bands of 150 and 275 KeV respectively; whereas respective increments during 14 July, 2011 are 3 times and 2 times only [Figure ??]. A close scrutiny of 02 April, 2011 event based on the observations from two geostationary satellites GOES 13 and GOES 15 show that both the satellites encountered the electron cloud at slightly different times. During the onset of substorm, GOES-13 and GOES-15 were located at 6 MLT and 5 MLT respectively, which means GOES 15 was closer to magnetic mid-night than GOES-13. An early encounter by GOES-15 confirms the eastward propagation of the electron cloud.

The magnetic observation of 02 April 2011 event clearly displays the absence of westward electrojet signatures during huge enhancement in the cosmic noise absorption level in the riometer data corresponding to substorm activity. During 1000-1400 UT, Maitri is located at the day side of the magnetosphere. Hence we would have expected that the precipitation may be due to longitudinal auroral oval expansion up to day side. Had this been the case, we would have seen the magnitude of auroral electrojet current at Maitri. In an event of strong geomagnetic storm, it is seen that the whole auroral oval is covered with westward electrojet (Anand et al., 2014). However, we dont see any kind of signatures in the H-component of geomagnetic field at sub-auroral station, Maitri during the present event. Hence, this DCNA event is not necessarily due to the ionosphic movement of plasma. Moreover, there is a certain delay of 24 minutes recorded between the onset of substom in the AL index and onset of CNA in the riometer data also enhanced electron flux was observed at GOES-13 located at 6 MLT. Therefore, absorption event can be attributed to Magnetospheric drift of the electrons.
Table 4.2: Geographic, geomagnetic Co-ordinates, L-values of NORSTAR and space weather service (SWS) Australian stations, taken for riometer observations

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<th>Geog.Long.(°E)</th>
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<th>CGM Long.(°E)</th>
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<td>11</td>
<td>-63</td>
<td>53</td>
<td>5</td>
</tr>
</tbody>
</table>

The magnetospheric drift of the electrons and protons in the equatorial plane is possible due to the gradient-curvature drift.

Figure ?? shows the can characteristics at longitudinally distributed stations inside the auroral oval during the substorm on 02 April, 2011. Geographic and geomagnetic coordinates of these stations have been given in Table ???. The stations were chosen in such a way that they fall in MLT sector between mid-night and Maitri, so that we can examine the electron precipitation at different longitudes during their eastward gradient-curvature drift. Initial selection of the stations for riometer data were chosen from Riometer and Imaging Riometer data base given by department of Physics, Lancaster University, UK (http://spears.lancs.ac.uk/cgi-bin/riometers). The left dashed line shows the onset of the substorm indicated by AL-index in the upper panel. Second to sixth panels from the top show successive delay in the onset time of CNA at longitudinally distributed stations. Please note that stations were plotted eastward from mid-night sector to day sector up to Maitri. MCQ being located at magnetic midnight during the onset of the substorm, ishowes immediate onset of CNA, which is mainly due to field line propagation of electron. However, there is a systematic delay in CNA onset at DAWS, FSIM, RABB, GILL up to Maitri as we move from west to east. DAWS, FSIM, RABB and GILL stations are almost equally spaced in MLT. Therefore, we should expect almost same time delay in the CNA onset as we move from one station to another from midnight to Maitri.
Figure 4.10: Onsets of CNA at stations in different MLT sectors between local mid-night to Maitri location (while approaching eastward) during the substorm onset on 02 April, 2011. Green arrow indicates the onset of substorm and CNAs at all the stations. Upper panel represents the AL-index and the rest lower panels represent the CNA onset at stations mentioned in Table-2
But, having different L-values, these stations show little offset from the expected delay time because electron cloud will take slightly more time for larger L-station as compared to smaller L-station belonging to the same MLT region. Additionally, the maximum value of CNA has consistently gone down from 3 dB (at MCQ) to 0.8 dB (at Maitri) as one proceeds from midnight to the day sector. This signifies the loss of electrons while drifting eastward. We have taken the delay time between the onset of the substorm and onsets of CNA at all the stations to estimate the energy range of the electron flux resulting into CNA at Maitri as well as at other stations.

In degree of magnetic longitude per second \( \left( \frac{M_{\text{long time}}}{\text{time}} \right) \), the bounce-average drift velocity of electrons in a dipolar field can be written as [Baharell et al., 2015]

\[
< W_d > = \frac{3LE}{22 \times 10^6} (0.7 + 0.3 \sin \alpha) + 4.17 \times 10^{-3}
\]

[See, e.g., Northrop, 1966], where \( E \) is measured in Re, the energy in eV, and \( \alpha \) is the equatorial pitch angle. The value is contribution from Earth’s rotation.

\[
t = \frac{\phi - \phi'}{< W_d >} + t' \tag{4.2}
\]

Now, \( t \) is time taken by an electron to reach at an azimuthal location \( \phi \) after gradient-curvature drift. For this event, one has to assume the injection of electron after onset at location \( \phi' \) in \( t' \) time [Beharrell et al., 2015]. The above equations clearly show that the drift time is inversely proportional to the energy of the electron flux. If we consider the CNA is produced due to the energetic electrons that drifted eastward in the equatorial plane due to gradient curvature drift, we have to estimate the energy of the electron flux that actually cause such absorption at L=5. To estimate the energy we can re-arrange the equation at (3) and can get the Energy equation,

\[
E = \frac{22 \times 10^6}{0.7 + 0.3 \sin \alpha} \left( \frac{1}{3L} \right) [< W_d > - 0.00417] \tag{4.3}
\]

\[
E = \frac{22 \times 10^6}{0.7 + 0.3 \sin \alpha} \left( \frac{1}{3L} \right) \left( \frac{M_{\text{long time}}}{\text{time}} - 0.00417 \right) \tag{4.4}
\]
Here, from equation (6), we can calculate the energy range of electrons that might have caused such precipitation. The upper and lower cutoff of are respectively taken as for the gradient curvature drift in the L=5 magnetic shell. Below =5 degrees, electrons may fall into loss cone and hence may not take part in the gradient curvature drift. For simplicity we use a single value for equatorial pitch angle, 450 the average pitch angle in an isotropic distribution. To calculate the drift velocity we have used the delay between the substorm onset and the onset of different stations such as at Maitri it is 24 minutes. Generally, particle injections occur at the magnetic mid night hours during susbtorm activity [Liang et. al., 2007; Lopez and Lui, 1990]. Hence we consider delay as the time of drift of the electrons to reach the location of Maitri. Therefore, the magnetic longitudinal difference of Maitri during the precipitation event will be 153.250. Hence, after putting all these values in equation (6), the expected energy of the electrons comes 160 KeV. Similarly, we calculated the expected energy of the electrons for the other stations. The range of energy of electron flux is found to be 160-290 KeV. This apparently matches with the GOES 13 electron flux observations. Large enhancement in the electron flux data was evident of same energy ranges 150 and 275 KeV which are towards to be nearest to the estimated energies. Additionally, pulsation studies of these two events show the presence of Pc5 oscillations on both days. It is clearly seen that the amplitude of Pc5 pulsation is significantly different for both the days. During the day side CNA, the peak-to-peak amplitude is 25 nT, whereas it is less than 8 nT on the non-CNA event, which is considerably less for this day. This simply explains that the energy transferred into the magnetosphere was higher during the CNA day. Enhanced IEF with increased conductivity during CNA day drives current resulting into increased pulsation amplitude. Hence, we could infer the energy input to the ionosphere also does play a role in controlling the day side absorption event.
4.6 Conclusions

The current study attempts to examine the detailed characteristics of identify DCNA events observed at Indian Antarctic station Maitri on 02 April, 2011. This day side CNA event is more intense and has larger duration than auroral substorm absorption event that was observed earlier (0530 MLT) on the same day at Maitri. Though day side CNA is related to susbtorm onsets, the susbtorm alone is just the necessary condition for the occurrence of such absorption event. Our comparative study of two substorm events of 02 April 2011 and 14 July 2011 and the detailed examination of DCNA event of 02 April, 2011 lead to the following key points:

- The initial comparison between the characteristics of auroral substorm absorption (ASA) event and the DCNA event at Maitri during 02 April, 2011 are distinctively different in characteristics. Absence of westward electrojet and delay between the substorm onset and onset of CNA during the DCNA event indicate different processes involved in ASA and DCNA events. Further, we compare two substorm events when Maitri was in day-side i.e. one resulting in CNA (02 April, 2011) and the other not showing any CNA signature (14 July, 2011). The comparison clearly brings out the fact that the substorm can only be the necessary condition to affect the DCNA.

- Comparison of interplanetary conditions between days of substorms of similar strength when Maitri was in the dayside suggests that longer sustainability (t) of higher eastward interplanetary electric field (Ey) favors the DCNA event. However, further statistical study is required to estimate the critical limit of Ey.t, above which DCNA can occur. This will form the part of our future studies.

- GOES-13 satellite observation of electron fluxes with 40-475 KeV energy range shows clear enhancement during substorms on both the days (02 April, 2011 and 14 July, 2015) when Maitri was on the dayside. However, electron flux in the energy band of 150 and 275 KeV during DCNA day have increased by many folds (at least more than 2 folds) compared to the day of 14, July, 2011.
Further study of electron cloud evolution for DCNA event (02 April, 2011) shows the eastward propagation of these electrons which are encountered by both GOES-13 and GOES-15 satellites (note that GOES-14 was operational in that day but data is not available).

5. For both those days, global presences of Pc5 oscillations were examined. During DCNA, strong Pc5 waves were globally observed. However, for the substorm event not resulting into DCNA, Pc5 wavelike structure was observed for a very short duration both at Maitri and other locations mentioned in Table 2. It should be noted that at Maitri the peak to peak amplitude of these oscillation is 3-4 times larger during DCNA event (1100-1300 UT of 02 April, 2011) than those observed for no DCNA event (1000-1200 UT of 14 July, 2011) as depicted in figure-8. This indicates the presence of pronounced Pc5 oscillations at Maitri facilitates the growth of VLF chorus waves, which in turn trigger the process of loss cone scattering resulting DCNA event through wave particle interaction as suggested by various researchers working in the area of wave particle interaction [A.N. Jaynes et. al., 2015 (reference therein); W.Li et. al., 2011; Kennel and Coronity, 1970].

Onsets of CNA at longitudinally distributed stations between the local magnetic midnight and Maitri shows systematic time delay. It confirms the precipitations of eastward drifted electrons are responsible for DCNA event. Further, delays between the substorm onset and onsets of CNA used as the time taken by the eastward drifted electron were used to compute the energy of drifted electrons. It was concluded that electrons in the energy range of 170 to 300 KeV might have taken part in the precipitation processes. The inference is in agreement with the observation from GOES 13 and GOES 15 satellites, which also show increment of electron fluxes in the energy band of 150 and 275 KeV.
Chapter 5

CNA response to the recovery phase of
2015 St. Patrick’s day geomagnetic storm

5.1 Introduction

Occurrences of geomagnetic pulsations in the Pc5 (2-7 mHz) range during the recovery phase of a geomagnetic storm is well studied among the researchers. Many workers such as Yamoto and Saito in [1980], Kivelson and Pu [1984] have suggested that the solar wind driven K-H instability (KHI) leads to such pulsations. Recently, Pilipenko et al [2010] have shown in his study that the generation of Pc5 waves are together done by high speed solar wind stream and elevated density fluctuation triggered KHI. Additionally, Philipenko [1990] has shown that Pc5 waves can be effectively triggered by energetic proton fluxes with non-Maxwellian distribution in energy and space. However, a statistical study done by Viall et al.[2009] showed that certain discrete frequencies in the solar wind are more favorable to produce Pc5 pulsations in the magnetosphere, globally. Presence of Pc5 pulsation can trigger interaction of particles with VLF waves, which can cause at high latitude gives rise to particle precipitation and subsequent CNA productions. Substrom onset, geomagnetic pulsations, whistler-mode VLF
and energetic particle precipitation are the simultaneous phenomena observed in the morning sector at the auroral latitudes [Li et al., 2015 and reference therein]. Moreover, Sometimes, pulsations are also seen in the cosmic noise absorption event [Spanswick et al., 2005]. A statistical study was done by Spanswick et al., [2005] with using NORSTAR riometer and CANOPUS magnetometer arrays to understand the modulation of high energy electron precipitation by ULF waves in the Pc5 frequency band. The study was conducted in two parts. One part has has explained the necessary conditions i.e presence of geomagnetic pulsation during the occurrences of pulsation in CNA by taking 11 years of data from three different stations. 95% of CNA pulsations occur during morning hour compared to occurrences of 70 % geomagnetic pulsations. When a geomagnetic pulsation occurs in a auroral location i.e Gillam [CGM (56.4°N, 265.4°E)] during dawn hours, 70 % chances are there to occur a corresponding CNA pulsation as observed in Riometer. CNA pulsation needs both favorable magnetospheric electron flux conditions and large enough magnetic Pc5 wave activity. Following the data survey of Baker et al.[2003], it was suggested that pulsations generated due to field-line resonances are more likely to develop CNA pulsations.

Predominantly, ULF magnetic pulsations play the major role in the energization and loss of higher energetic electrons in the dawn sector of auroral oval [Helliwell, 1965; Kimura, 1974; Sato et al., 1974; Sato and Fukunishi, 1981]. These ULF waves, together with VLF-chorus waves encourage such high latitude precipitations. In fact, both chorus and hiss can drive particle precipitation at higher L-values [e.g., Heimeng Li at. al., 2015; Golkowski and Inan, 2008; Bortanik and Thorne, 2007 ]. The main mechanism behind such precipitation is the electron-cyclotron resonance and subsequent pitch-angle diffusion. Theoretical explanation as well as modeling of cyclotron resonance of VLF waves and precipitating energetic electrons with an energy range from tens of KeV to more than 1 MeV has been done [Bortanik and Thorne, 2007]. Additionally, Lorentzen et al. [2001] through satellite observations established the relation between VLF-Chorus and relativistic electron microburst. Tsurutani and Smith [1977] have analyzed the latitudinal and local time distribution of extremely low
frequency (10-1500 Hz) chorus to determine dependence on substorms and showed that equatorial chorus is related to substorm. However, in the present study we have observed VLF-Hiss occurred during the substorm activity at high latitude and have presented in this study. Other study also shows that interaction of relativistic electrons with electromagnetic ion cyclotron (EMIC) mode waves in the inner magnetosphere [Rodger et al., 2008; Miyoshi et al., 2008]. EMIC waves are the highest frequency electromagnetic waves in the ULF spectral regime. They are observed in ground-based observations as Pc 12 (0.15 Hz) waves and sometimes extend to frequencies above 5Hz in space-based observations. EMIC waves are significantly more likely to occur during geomagnetic storms, with the largest amplitude waves occurring in the duskside sector.

Objective

So far many workers have shown the different colors of the geo-effectiveness during 17th March storm, 2015. Worker such as Singh et al, 2015 has shown the low latitude impact with in the Indian sectors Singh et al [2015]. Tulasi ram et al [2016] has shown the pronounce equatorial zonal electric field enhancement in response to prompt penetration of eastward convection electric fields(PPEF) during this geomagnetic storm. The mechanisms are thought in terms of unique electrodynamic conditions prevailing at dusk sector in the presence of convection electric elds associated with the onset of a substorm undersouthward interplanetary magnetic eld Bz. Workers such as Iurii Cherniak and Irina Zakharenkova [2015];Astafyeva et. al [2015] have shown the high latitude impact during the main phase of the storm. But, this work is mainly based on the observations during the first recovery day (18th March,2015)of the St. Patrick’s geomagnetic storm. The main phase has been beautifully explained by above workers. Nevertheless, we are also giving some of the important and almost similar details of the main phase of the geomagnetic storm. Detail elaborate of the storm is done by Kamide and Kusano [2015]. Coming to recovery phase of the the largest storm of the ongoing solar
cycle, it has an extended recovery phase.

In the current study, we have concentrated in the first recovery day of the largest strom. Sudden enhancement in CNA was observed at the post noon hours (1500-1800 UT) at Maitri Antarctica with little signature of eastward electrojet together with VLF-chorus signature at Halley station (geog.75.58°S, 26.233°W) is matter of concern. Further, we also observe the presence of geomagnetic as well as CNA pulsations during first recovery phase day with some peculiar characteristics. Global characteristics of during this period was examined with the help of IMAGE chain stations. In order to identify the cause and effect relationship between the geoamgetic pulsation and CNA pulsation at Maitri, we have used a noble approach based on Transfer Entropy method.

5.2 Data set

The Imaging Riometer and DFM are operated together at Maitri to study the substorm related particle precipitation characteristics and the dynamics of auroral electrojet current systems. To identify the substorm onset time and its strength, we have used AL-index and Wp-index from the WDC, Kyoto site. Recently, Wp (Wave and Planetary) index has been introduced by Nose et al. [2014] as a new and more authentic indicator of substorm onsets [Thomas et. al., 2015]. This index shows the wave power of the Pi2 pulsation at low latitude, which was derived from geomagnetic data from 11 low latitude stations. Singh et. al. [2012] has shown the importance of fixing criteria on AE/AL index enhancement/depression to identify a substorm. For identifying substorm onset, we impose the condition on AL that there should a transient depression of more than 150 nT within a time span of 2 minutes. SYM-H and DST-index data have been used as a proxy for the ring current enhancement during the course of the observed events. For interplanetary parameters such as interplanetary magnetic fields, solar wind velocity, interplanetary electric field etc., data have been taken from the OMNIWEB data centre (http://omniweb.gsfc.nasa.gov/form/omni_m.in.html). The in-situ
measurements of energetic electron flux injections have been obtained from GOES-13 satellite. We have used data from Halley station (geog.75.58°S, 26.23°W) for VLF observation. The station is \( \sim 03\text{hr} \) west to the Maitri station but in the same CGM lat as Maitri.

5.3 Observations

Figure 5.1 is showing the interplanetary conditions and the ground observations during the largest geomagnetic storm of the current solar cycle.

5.3.1 17\textsuperscript{th} March geomagnetic storm event

Many workers such as Luric Cherniak and Irina Zakharenkova, [2015]; Y. Kamide and K. Kusano [2015]; Elvira Astafyeva et al, [2015]; Singh et. al., [2015]; Tulsiram et al. [2016] have discussed the St. Patrick’s day storm with allied research. Each author has given a nice description of the storm which of course, included interplanetary as well as ground observations. Here also we have given a brief observational details to the geomagnetic storm periods which includes recovery phase also. Our interest lies in the first day of the recovery phase and hence we have explained the interplanetary and ground observation of the 18 March 2015 in details. The storm which started on 17 March 2015 on St. Patrick’s day is classified as G4 (severe) level storm (http://www.swpc.noaa.gov/noaa — scales — explanation). The storm was so huge that red aurora was observed upto Northern part of Japan for the first time during the current solar cycle. Interestingly, the 17-18 March 2015 storm was not associated with any major x-class or M-class flare [Y. Kamide and K. Kusano, 2015] which is taken as precursor. This may be key reason for not able to predict the severe geomagnetic storm by major agencies such as space weather agencies by United States, Japan, and Europe.
Figure 5.1: St. Patrick day’s geomagnetic event

Figure ?? illustrates the St. Patrick’s storm during 17 – 19 March 2015. Upper four panel represents the interplanetary conditions such as solar wind ($V_s$), $B$ and $IMF - B_z$, plasma density ($n_s$) and solar wind pressure ($nPa$) respectively. Bottom two plots show the ground signatures. $AL$ and $AE$ shows the localized disturbances in the auroral oval where as global
response can be seen in $DST$ index. This storm came with a sudden storm commencement (SSC) at $\sim 0445$ UT and the main phase has started which can be seen in DST index. The main phase has dropped down to its minimum value of $-226$ nT at $\sim 2300$ UT with couple of localized depressions of $-93$ nT and $-164$ nT at $\sim 0940$ UT and $\sim 1740$ UT respectively [Luric Cherniak and Irina Zakharenkova, 2015]. Interplanetary behavior was very dynamic in the main phase of the storm. Solar wind has started picking before the main phase of storm up to $\sim 1700$ UT and showed slow recovery up to 2400 UT of 17 March 2015. Later on it started slowly picking up and maximize at $\sim 2200$ UT during 18 March, 2015. it showed a kind of sinusoidal behavior. Interplanetary magnetic field showed enhancement right after the $SSC$ and maximized up to 20 nT at 1500 UT. In particular,$IMFBz$ was very much fluctuating during the main phase. The details of these fluctuations were provided by Elvira Astafyeva et al [2015]. Here we would like to discuss more on the recovery phase. During the recovery phase, $IMFBz$ was still fluctuating but with less intensity. The minimum value of $IMFBz$ was $\sim -10$ nT which was almost half of the intensity occurred during main phase. Interestingly, solar wind density and solar wind pressure showed very steady behavior right after the end of main phase. They were completely different from the behavior during main phase, where solar wind density and solar wind pressure had risen up to $\sim 60/cc$ and~ $40nPa$ respectively. The average values of solar wind density and solar wind pressure during the recovery phase were less than half of the values obtained during main phase in the recovery phase. This confirms the steady recovery of the magnetosphere. The ground observations were also in agreement of the above fact. Auroral indices showed significant reduction in the intensity. For example, minimum value of $AL$ was $\sim -2000$ nT and maximum value of $AE$ was $\sim 2000$ nT during the main phase, where as $AL$ was $\sim -1200$ and $AE$ was $\sim 1200$ nT during the first recovery phase (18 March 2015). Nevertheless, among many substorms during first recovery phase, the largest substorm was $\sim 1400 – 1800$ UT. In order to understand the energy that enters into the magnetosphere during solar wind-magnetosphere coupling, Elvira Astafyeva et al [2015] have shown the behaviour of polar cap index ($PCI$). The results showed the increases of the polar cap magnetic activity started at 06 UT and at
09 UT and then four other intense peaks at 14, 18, 21, and 23:30 UT on 17 March. During these periods of time, the PCC index reached 1015 that indicates an extreme substorm activity during the storm [Troshichev et al., 1988, 2006]. Furthermore, close observation of $PC$ index clearly showed comparatively less enhancement during the first day of recovery phase of the storm. These facts suggest that the energy transfer into the magnetosphere reduced from the first recovery day onward reduced. However, the observation at Maitri during the first day of the recovery day suggest huge CNA event and even more than the CNA occurred at Main phase.

5.3.2 Observation at Maitri during storm

In this sections, the riometer and magnetometer observations at Maitri, Antarctica during the geomagnetic storm are thoroughly discussed. The geomagnetic storm has been associated with number of substorm onsets. The detailed criteria for substorm identification has been fully explained in chapter-4. Figure ?? shows a number of substorm onsets during the storm. It is clearly observed that the intensity and occurrence frequency of substorm onsets reduced as the storm progressed. We observed substorm onsets with less intense and less frequent in the recovery phase compared to the main phase. Hence one can expect the field line precipitation of electrons would subsequently reduce with the initiation of recovery phase. As CNA is linked to the electron precipitation at auroral oval including Maitri, we expect the the reduction in the CNA production at Maitri with the initiation of recovery phase.

Figure ?? depicts the observations at Maitri during the period of 17-19 March 2015. The top three panel represents the variations in H, D and Z components obtained from DFM respectively. The fourth panel shows the CNA strength. The CNA strength was obtained by subtracting the riometer signal for the disturbed days ($17 \rightarrow 19 \text{March}$) to the QDC of the March month of 2015. The bottom most panel is showing the keogram of the imaging riometer which provides the image plot CNA across the field of view ($\sim 200 km \times 200 km$).
Figure 5.2: Multiple onsets of substorm during the storm. Upper panel shows AL/AU index for the duration of 15-20 March, 2015. The lower panel shows the storm for the same duration of imaging Riometer at \( \sim 90 \) km altitude. Significant intensification of westward electrojet is seen as observed the depression in the H-component at Maitri. Generally, intensification of westward electrojet has nice correlation with the substorm onset during mid-night to morning hours (Behera et al., 2015). Being Maitri located at the equatorward of the standard auroral oval, often it comes under the influence of substorm related westward electrojet. The first onset of westward electrojet is seen at 0700 UT which coincides with the substorm onset during the main phase of the storm. The next large westward electrojet intensification is seen \( \sim 1600 \) UT of 17 March to 0800 UT of 18 March centered at mid night. Similarly, westward electrojet intensification is seen during 2000 UT of 18 March to 0800 UT of 19 March. Note that intensification of westward electrojet has significantly reduced with the advent of recovery phase. The maximum electrojet value was \(-1200\) nT which centered at 17 March mid night, where as it was only \(-300\) nT for the next mid night. Intensification of
substorm also reduced with the proceeding of storm. CNA enhancement is seen right from the
first onset of substrm along with the intensification westward electrojet. Image of CNA also
shows the localized enhancement during the onset of the storm. These images are patchy and
do not cover the full field of view(FOV) of the imaging Riometer. However, pronounced CNA
productions are observed during the intensification of westward electrojet which centered
around 17 March mid-night. The maximum value of CNA obtained is $\sim 2.1$ dB. Multiple
CNA onset spikes along with background CNA enhancements are observed. These spikes
are related to field line precipitations of electrons in the night side. Finally CNA came to its
minimum value at 0800 UT of 18 March,2015. There after again CNA level rise, but with
the absence of any westward electrojet. During 15-18 UT, we have observed a sudden CNA
enhancement which is even larger than the maximum CNA enhancement observed during the
main phase of the geoamgetic storm and forms one of the main focuses of the current study.
For further study, we have presented the filtered CNA and H-component data in the Pc5 band (2-7 mHz) during 18 March 2015 as shown in figure 5.3. The upper most panel shows the filtered data of H-variation followed by filtered CNA data. To compare the onset of CNA and related Pc5 wave power, wide beam CNA data has been plotted in the bottom most panel. It can be seen that geomagnetic pulsation is present throughout the day, but with varying amplitudes. Similarly, we see multiple burst of Pc5 in the CNA data. However, it is not continuous like geomagnetic pulsations, for example, no pulsation activity can be seen during 0600-0900 UT and 1800-2200 UT (please refer middle panel of fig. 5.4). Interestingly, only those time sectors have no Pc5 activity where CNA is at its minimum level. Hence, one can suspect the possible relation between the pulsation activity and the level of CNA.
production. Additionally, it is seen that the largest and prolonged Pc5 burst in the CNA data during 1500 – 1800 UT. We also observed burst in the geomagnetic pulsation during the same time. Among geomagnetic Pc5 burst during 18 March 2015, the strongest burst is observed during 2100-2400 UT, but there is no simultaneous Pc5 oscillations in CNA data.

Figure 5.4: Upper panel and middle panel show the filtered H and CNA in the Pc5 band (2-7 mHz) during 18 March, 2015, respectively. The bottom most panel represent the wide beam CNA during 18 March, 2015.
Table 5.1: Geographic and geomagnetic co-ordinates of the IMAGE stations, taken for global Pc5 observation

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5.3.3 Latitudinal and longitudinal IMAGE chain observations

The IMAGE (International Monitor for Auroral Geomagnetic Effects) chain stations are precisely meant to monitor the auroral electrojet dynamics within and around the standard auroral oval. It covers a geographical latitudinal range of 54 – 79° N. Figure ?? depicts the H-variations during 18 March, 2015 at some of the image chain stations with decreasing latitudes from top to bottom panel in the fixed longitude range of 102 – 106° E longitude along with filtered data in the Pc5 band (2-7 mHz) at their right side respectively. The detailed of the stations are given in table ?? . The left plots of figure ?? are clearly showing no signatures of any electrojet is seen after 0300 UT up to 1400 UT. However, presence of eastward electrojet is clearly seen at the stations such as PEL, OUJ and HAN 1400 UT onward with decrease in intensity with sliding down the latitudes. For example, Pel shows of maximum intensity of ∼ 500 nT, where as TAR only shows of ∼ 30 nT only.

This suggest that the onset location of the substorm is within the auroral oval but equatorward. In other words, substorm onset occur near PEL station which has the same latitude as of Maitri station. The dashed lines are indicating a time period of 03 hours when huge precipitation is been taken place at Maitri. Hence we would expect the presence of direct precipitation at the location of Maitri during this time duration. The right side plots of the figure ?? show wave power of Pc5 pulsations decrease with down the latitudes. Almost no
Figure 5.5: Left figure represents the H-variation at different IMAGE chain stations with decreasing order of latitudes, where as right figure shows their filtered data in Pc5 band, respectively.
CHAPTER 5. (CNA) response to 2015 St.Patrick’s day storm

Table 5.2: Geographic and geomagnetic co-ordinates of the IMAGE stations, taken for eastward electrojet signature and global Pc5 observation

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</table>

sign of Pc5 waves are seen at Tar station.

The presence of eastward electrojet at Maitri is shown in figure ?? and discussed in this section more clearly. Figure ?? depicts the H-variation at the longitudinally distributed stations with similar latitude as Maitri in order to examine the characteristics of eastward electrojet during 1500 to 1800 UT. Clear simultaneous onsets of eastward electrojet at stations SOD, PEL, JCK and DON are evident. The onset time is ∼ 1400 UT at SOD. However, a delay of ∼ 01 hr is seen at Maitri. Maitri is more away from local mid night sector and more of eastward which forms the delay in the onset of eastward electrojet at Maitri. Additionally, the intensity of the eastward electrojet reduced with its longitudinal propagation. The right plots of figure ?? show the filtered H-variations in the Pc5 band same like figure ?? for the respective left panel station. H-variation and filtered H-variation data for Maitri have been colored in blue and filtered CNA data for Maitri with red for the duration of 1500 -1800 UT. It is event that geomagnetic and CNA pulsations are simultaneous occurred at Maitri, where as no other station of IMAGE chain show similar Pc5 burst around that interval (1500 -1800 UT). In figure ??, it was already seen that CNA pulsations is most pronounced during this interval.
Figure 5.6: Left figure represents the H-variation at different IMAGE chain stations including Maitri station with decreasing order of latitudes (Maitri is shown in blue color), where as right figure shows their filtered data in Pc5 band, respectively. Again Maitri is shown in blue color. Additionally CNA data at Maitri filtered at Pc5 band has shown in red color at the bottom most panel of right figure.

5.3.4 Magnitude-squared coherence and cross spectrum phase

In order to study the characteristics of these Pc5 oscillations, magnitude-squared coherence (msc) and cross spectrum phase analysis were done. The spectral coherence can be used to examine the relation between two time series. Figure ?? is showing the msc and cross spectrum phase of the filtered time series of H-component of magnetic field and CNA at Maitri during 1500 – 1800 UT. The msc analysis confirms the presence of high coherence at frequencies 2.5
CHAPTER 5. (CNA) response to 2015 St. Patrick’s day storm

MHz, 3.1 mHz and 3.6 mHz between the geomagnetic and CNA pulsations. Interestingly, we see almost no phase lag between the geomagnetic pulsation and CNA pulsations for those frequencies which show high coherence (>0.8). This creates a puzzle when we try to understand the cause and effect relation between the geomagnetic pulsation and CNA pulsations. In order to find the cause and effect relation, a novel technique has been introduced which is discussed in next section. Nevertheless, msc and cross phase spectrum has confirmed high coherence between the geomagnetic and CNA pulsation.

Figure 5.7: Magnitude squared Coherence of two time series i.e H and CNA at Maitri for the period of 1500-1800 UT is shown in the upper panel. The phase lag between these two time series is presented in the lower panel.

5.4 Discussion

It is the first observation of pronounced CNA production along with simultaneous geomagnetic pulsation and CNA pulsation at a station (Maitri, Antarctica) during the St. Patrick’s
day geomagnetic storm of the year 2015. Maitri is situated at the lower fringe of auroral oval and its ionosphere only responds to the moderate to larger substorms. Mainly storm-time substorm are able to alter the state of ionosphere over Maitri, Antarctica (Jayanta et al., 2015). Interestingly during the largest geomagnetic storm of this current solar cycle, it is observed that the production of CNA at high latitude during the recovery phase can be larger than that of the CNA during the main phase of the storm. We showed interest particularly during the time window of 1500-1800 UT on 18 March 2015 (first day of the recovery phase). Additionally, we see the presence of geomagnetic pulsations and pulsations in riometer during 18 March 2015. Pulsations with larger wave power and longer duration coincided with the largest production of CNA during 1500-1800 UT. However, the wave power of corresponding geomagnetic pulsations were similar to the other burst in that day.

Even though the interplanetary conditions were quite steady and less dynamic compared to the main phase. Still the interplanetary parameter such as solar wind (\(V_s\)), \(IMFBz\) and corresponding \(IEFEy\) were large. As our interest lies in the window of 1500-1800 UT, so it will be interesting to see the relative interplanetary condition in this window compared to rest of the day of 18 March 2015.

The production of large CNA during afternoon sector at Maitri and its possible cause is the central theme of this study. Many literatures have suggested that precipitation and related CNA enhancement at high latitude particularly at \(4 < L < 7\) during storm time substorm is possible due to direct field line precipitation of \(\sim\)KeV electrons. Also, wave-particle interactions such as VLF and sub-relativistic electrons in the presence of ULF waves can scatter charge particles and subsequently lead to precipitations as shown in previous chapter 4 or/and Electron Magnetic Ion-cyclotron(EMIC) waves scattered relativistic electrons precipitation [Rodger et al., 2008; Miyoshi et al., 2008] can also be the cause of such large afternoon CNA at Maitri. The whistler-mode chorus is typically observed in a series of short rising tones in the frequency range of \(\sim\)12.5 kHz outside the plasmapause predominantly in the dawn sector. Chorus can be a driver of energetic electron precipitation [e.g., Pasmanik and Trakhtengerts, 1999; Trakhtengerts and Rycroft, 2000; Bortnik and Thorne, 2007; Golkowski and
Inan, 2008] due to the electron-cyclotron resonance and pitch-angle diffusion. The pitch-angle scattering of the radiation belt energetic electrons by chorus can lead to significant precipitation into the atmosphere [Lorentzen et al., 2001; Meredith et al., 2001; Summers, 2005]. Tsurutani and Smith [1974] and Anderson and Maeda [1977] found that the onset of the chorus emissions coincided with the injection of substorm electrons with energies of $\sim 10^{10}$ keV. Additionally many literature also suggest that hiss waves can occur inside the plasmasphere and become stronger during substorms [Smith et al., 1974; Thorne et al., 1974a, 1974b; Meredith et al., 2004]. These plasmaspheric hiss can scatter the energetic electrons into the loss cone, the plasmaspheric hiss waves are important to the loss process of energetic electrons in the inner magnetosphere [Titova et al., 1998; Summers et al., 2008; Yuan et al., 2011, 2012a, 2012b]. Plasmaspheric hiss is a wide band, no structural ELF emission with a typical frequency band ranging from about 100 Hz to several KHz. We have tried to see each factor that may lead to precipitation and related CNA enhancement during 1500-1800 UT on 18 March, 2015. Figure ?? is showing the the dynamic spectra of VLF data from Halley station ($75.58^\circ$ S, $26.233^\circ$ W) for the duration of 1200–2030 UT on 18 March, 2015. Halley station is nearer to Maitri in terms of geographic as well as CGM latitude, but with different longitudes. It is $\sim 03$ hrs west to the Maitri station. The dynamic spectra of VLF data clearly shows the presence of hiss during the period of 1500-1800 UT when large CNA has occurred at Maitri. First hiss burst can be seen during 1400–1500 UT, later contineous occurnace of hiss can be seen up to 1800 UT. Several burst can been seen above 1 KHz, however they can not be termed as chorus as they do not have any consistent structures as shown by Manninen et. al., [2010]. Also, observation of VLF related precipitation during afternoon hours is not common. During afternoon hours and late evening hours, precipitation due to EMIC wave is literally evident. Hence we have look in to the presence of EMIC wave at Maitri. Unfortunately, we do not see any EMIC wave presence during these hours. Additionally, Figure ?? and ?? shows of clear presence of eastward electrojet at Maitri during 1500-1800 UT. Hence we believe these two processes e.g. VLF scattered subrelativistic electron precipitation in the presence of ULF wave and direct field line precipitation seen as eastward electrojet together
might have produced such huge CNA in the afternoon hours at Maitri.

Figure 5.8: Dynamic spectrum of VLF data from Halley(75.58° S, 26.233° W) for the duration of 1200-2030 UT is shown here

**Entropy method to evaluate the cause and effect**

As discussed, for the huge CNA during the first day of recovery phase of March 17, 2015 storm, we observe the presence of geomagnetic pulsations and CNA pulsations, in H-component of geomagnetic data and imaging Riometer data from Maitri, respectively. The geomagnetic pulsation were significantly occurred during the first recovery phase day. Whereas, CNA pulsations were seen to be present during high production of CNA on 18 March 2015. That simply describe an disturbed plasma system which may get modulated by the field line oscillations [Pilipenko, et al 1990]. However, worker such as [Sato and Mat-sudo ,1986] have shown the geomagnetic pulsation modules CNA pulsation are not always true. In order to find the cause and the effect in these two pulsations, we have adopted a noble technique called Entropy method.

Transfer entropy (TE) introduced by Schreiber, 2000 overcomes exclusively quantifies actual
information exchanged along with the directional flow of information between any two vari-
ables [Schreiber, 2000, De Michelis et al., 2011]. Therefore, it can be utilized for determining
the cause and effect relationship between two variables [Das Sharma et al, 2012, Vichare et.
al, 2016]. The more details of this technique can be found in Vichare et. al, 2016. Here, TE
is applied to establish what is the driver and response from the pair, geomagnetic pulsations
observed in magnetometer and riometers. Note that RIO acts as a good proxy for the particle
precipitation and H-component is a good proxy for magnetic field line oscillations. Both the
dataset show the periodic variations of almost same frequency which posed the question who
drives whom?

The filtered time series of time window 1500 – 1800 UT are considered to compute TE. As
data is filtered the resultant time series are stationary in nature and TE can be applied. Data
was down sampled to 10 sec resolution. TE is computed in both the direction i.e from geo-
magnetic pulsation to pulsation observed in riometer and vice a verse. The significance level
is estimated by following surrogate data test. The TE values are shown in figure ?? with
significance level. Estimated TE values are statistically significant. The figure clearly shows
there is maximum information flow observed from H to RIO at time lag 160 sec and for most
of the time lags the TE values for H to RIO are higher compared to RIO to H. This implies that
there is a net information flow from H to RIO. Thus, establishing that geomagnetic pulsation
modulates particle precipitation observed at the station with the time lag of 160 sec. Further
study needed to understand the underlying physical mechanism and the observed time lag.
Figure 5.9: Transfer entropy between two time series i.e H and CNA data of Maitri for the duration of 1500-1800 UT of 18 March 2015

5.5 Conclusions

The current study has attempted to understand the sudden rise in CNA level during the recovery phase particularly at 1500 – 1800 UT of the largest geomagnetic storm. Here high latitude observations of 2015 St. Patrick’s day geomagnetic storm have been thoroughly discussed. The storm that occurred at 17th March, 2015 is the strongest geomagnetic storm of the current solar cycle and had a longer recovery period. It is seen that production of CNA
is pronounced during the main phase of the storm, however the CNA enhancement in the first day of recovery phase, particularly 14-17 MLT at Maitri is larger than main phase CNA. Simultaneity of CNA pulsations with geomagnetic pulsations during the same hours is also evident. VLF observation from the Halley station (75.58 S, 26.233 W) confirms the presence of VLF-hiss ($\sim 400\text{Hz}$) during 15-18 UT. Interestingly, absence of Electro-magnetic Ion-cyclotron (EMIC) waves confirms the role of VLF-hiss for such huge CNA. Additionally, signature of enhanced eastward electrojet at Maitri during 14-17 MLT at Maitri is considered to be a additional factor for such large CNA. Further, study of geomagnetic pulsation activity were being carried out latitudinal and longitudinally with the help of IMAGE chain stations. To identify the cause and effect relationship between the geoamgetic pulsation and riometer pulsation at Maitri, a noble approach i.e Entropy which confirms the modulation of cosmic noise absorption due to the geomagnetic pulsations.
Chapter 6

Conclusions and future work

Certainly, this thesis is first of its kind to introduce imaging Riometer for the upper atmospheric study at Indian Antarctic station Maitri. It is not unknown to the scientific community, at least to those who deals with the study of space weather and geomagnetism, that A.P Mitra and C.A. Shain [1953], two Indian scientists introduced the Riometer technique for remotely sensing the state of the Ionosphere. They could be able to convince that this technique enables to make easy and accurate measurements of the total attenuation suffered by a radio wave while passing through the ionosphere, they also showed that two main contributions, from the $D$ and $F_2$, regions, can be recognized and separated. However, it was later confirmed that major contribution comes from the D-region during the cosmic noise absorption events [Kellerman et. al, 2009]. It was unfortunate that this research was not carried forward further in India. Significant advancement in the technique was suggested by Detrick and Rosenberg [1990] by introducing phased-array of narrow beam riometer antennas in order to obtain spatial and dynamic structure of CNA. Maryland University made initial progresses in this area and it built the first 64-element phased array system and deployed at South pole in 1988. Over the time, Lancaster group has taken over the lead and progressed as a strong research group in this field. Therefore, this work can be considered as a new beginning in India again to make a mark in this field. However, the situations are not the same as earlier, we
need to do multiple instrumental study in conjunction with imaging Riometer to justify and complement the observation from imaging Riometer. Nevertheless, some of the major events based as well as statistical observations are presented in this thesis along with the validation of the data from the installed set up. Additionally, this thesis is collection of first hand trials in the field of wave-particle interactions induced particle precipitations and related CNAs.

In chapter-2, a detail description of the imaging Riometer set up at one of the most difficult place Antarctica has been done with brief instrumentation. Theory of measurements of cosmic noise absorption and its interpretation has also been discussed. To validate any research, one must do initial work out such as quiet day patterns and seasonal variations analysis. Consistent shift of 2 hr in the diurnal pattern of quiet riometer singal pattern validate the data set and encouraged to proceed further with the research in this field of Riometry. Seasonal variations of quiet riometer signal pattern show consistency with some anomaly which were difficult to explain with limited data sets and it is beyond the scope of the thesis. Further comparing of these CNA events during isolated substorm and storm time substorm shows clear differences in the level of the CNA enhancement and also image describes the areal coverage of such enhancement in the field of view of the Riometer. Even though the Maitri is located at a sub-auroral station or the station equator ward of the auroral oval, statistics shows that their occurrences and strength predominantly affected by susbtorm.

Though various kind of CNA events were observed at Maitri owing to different physical processes involved for their production, chapter-3 has precisely focused the CNA event that occur during local mid night regions of Maitri. A statistical study has been carried out to understand the characteristics of substorm related CNA and their relation to the interplanetary conditions. Substorm related CNA is seen to occur mostly in the post mid night hours (02MLT). Intensity of the westward electrojet and CNA over Maitri were almost linearly related to the intensity of (northern hemispheric) AL index. At Maitri, westward electrojet and cosmic
noise absorption were mainly observed during storm-time substorms possibly due to the location of the station near equatorward boundary of the auroral oval. A clear distinction in the intensity and extent of the absorption region was observed for isolated substorm and storm-time substorm cases. Usually storm-time substorm absorption events were far more intense and covered wide latitude and longitude regions. Magnitudes of the southward IMF Bz combined with solar wind velocity or duskward IEF Ey were linearly related to intensity of CNA at Maitri. Moreover, increasing solar wind speed and IMF Bz appear to cause enhancement in the precipitation of harder electrons leading to enhanced CNA.

In chapter 4, I have focused on daytime (DCNA) CNA that is caused by wave particle interactions resulting the precipitation of charge particles. Statistics showed that occurrences of these events were rare and present during the day time. Absence of westward electrojet and significant delay between the onset of the substorm and the onset of the CNA at Maitri discard the role of direct precipitations of the energetic electrons which set Birkland current and current wedge at the onset of susbtorm. Further examinations clearly suggest that the role of equatorial eastward drifted electrons in the energy range 170-300 KeV are responsible for such day side CNA events. Again the presence of significant Pc5 pulsations with high amplitude confirms the role of wave-particle interactions lead to particle precipitation at Maiti triggered by ULF waves.

In Chapter-5, high latitude observations of 2015 St. Patrick’s day geomagnetic storm have been thoroughly discussed. The storm that occurred at 17th March, 2015 is the strongest geomagnetic storm of the current solar cycle. It is seen that production of CNA is pronounced during the main phase of the storm. However the CNA enhancement on the first day of recovery phase, particularly during 14-17 MLT at Maitri is larger than the main phase CNA. Simultaneity of CNA pulsations with geomagnetic pulsations during the same hours is also evident. VLF observation from the Halley station (75.58 S, 26.233 W) confirms the presence
of VLF-hiss (\(\sim 400\text{Hz}\)) during 15-18 UT. Interestingly, absence of Electro-magnetic Ion-cyclotron (EMIC) waves confirms the role of VLF-hiss for such huge CNA. Additionally, signature of enhanced eastward electrojet at Maitri during 14-17 MLT at Maitri is considered to be a additional factor for such large CNA. Further, characteristics of geomagnetic pulsation activity were examined with the help of IMAGE chain stations during the event. To identify the cause and effect relationship between the geomagnetic pulsation and CNA pulsation at Maitri, a noble approach i.e Entropy method was employed, which confirms the modulation of cosmic noise absorption due to the geomagnetic pulsations.

### 6.1 Scope of future work

As mentioned in chapter 2, the enhancement of CNA level during local magnetic midnight time produced by substorm activity greatly depends upon the intensity of duskward interplanetary electric field, instead of individual interplanetary parameter such as Vs and IMF Bz. However, inclusion of time integral of interplanetary electric field and the geometry of clock angle of interplanetary magnetic field were not considered. A thorough and careful checking of these parameter and further comparison with CNA enhancement data may give better picture of their relationship. Imaging Riometer at Maitri is now in continues operational mode and hence it would be a great idea to take a longer data set for the proposed study. Additionally, presence or absence of geomagnetic activity should be counted for the completion of the work.

I must confess that imaging aspect of the imaging Riometer was not extensively used. However, in some studies such as studies described in chapter 2 and 3, importance of the imaging aspects of CNA have been mentioned. Not many important studies have been carried out so far in the current scenario. Hence, extensive exploration of imaging technique to study CNA propagation, spatial and temporal structures of CNA at Maitri would do justice to the imaging Riometer set up at that distant location.

Features of day side cosmic noise absorption were described and possible reason for such
CNA was found to be eastward drifted sub-relativistic electrons. The conclusion given in the chapter 3 is that VLF chorus and drifted electron interact with each other in the presence of ULF caused such day side CNA events over Maitri. Day side absorption are linked to the precipitation of sudden injected electron flux during the substorm. However in another substorm, DCNA was not evident because of lack of electron flux and Pc5 activity. Hence it would be a great idea to investigate the possible scenario for the occurrence of DCNA in the light of above parameters, statistically.

Many worker [e.g. Rodger et al., 2008; Miyoshi et al., 2008; Meredith et al. 2003 ;Anderson et al., 1992; Anderson, 1995] suggested that the precipitation process at high latitude ($3 < L < 7$) are not only caused by wave-particle interaction by VLF chorus but also done by EMIC waves. However, these events are localized in the dusk and night sector. EMIC waves can be detected with searchcoil magnetometer operational at Maitri and hence their role in precipitating particles in certain energy band can be fruitfully examined by corroborating with the imaging Riometer data.
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Synopsis

Earthward Galactic Radio emission also called 'cosmic radio noise' from our galaxy including other galaxies and distant stars was incidently discovered by Karl Guthe Jansky and later on has been used as a tool to examine the state of the lower Ionosphere. The trans-ionospheric propagation of these cosmic radio wave leads to partial loss of its energy. The reduction in the cosmic noise signal due to ionspheric absorption or, Cosmic noise absorption events deal with mainly high latitude phenomena caused by the precipititation of high energy electrons and protons into the atmosphere where they cause excess ionization; at low altitudes (Stauning, 1996). Normally, the processes causing ionspheric absorption of radio waves take place at altitudes in the range of 60 to 100 km. Sometimes, extremely high energy protons created during solar flares and highly energetic electrons generated during substorms may produce significant ionization below 60 km of altitude. The absorption associated with the precipitation of energetic particles, is most intense in the auroral and polar regions. However, this absorption under certain conditions can get intensified at sub-auroral latitudes as well. These energetic particles constitute an important part of basic solar and magnetospheric physics. They are important as they can be tracer particles in a number of solar-terrestrial research fields, such as investigations of magnetospheric boundary properties, the distinguishing between open and closed magnetospheric regions, and other essential geomagnetic morphological problems. Moreover, theses high energy charged particles are essentially the consequence of the substorm processes and hence can be helpful in studies of substorm dynamics including various aspects of wave-particle interactions (Kavanagh et al.,
In addition to causing ionospheric absorption of radio waves, the energetic particle radiation may have various other noticeable effects on space systems, on communications, and on the environment etc. The high energy particle precipitation, furthermore, increases the conductivity of the atmosphere thereby changing its global electrical properties. The precipitation may even modify the lower atmospheric chemistry and composition such as, for instance, the nitric oxide and ozone abundances. The high energy precipitation events, on the other hand, offer essential advantages for atmospheric observations.

Riometer observations of ionospheric radio wave absorption were initially made using simple widebeam antennas [Little, 1954; Little and Leinbach, 1958]. Complex and variable nature of high latitude absorption processes, and later the need for detailed comparisons with other geophysical disturbance phenomena, such as auroral substorms further promoted the development of sophisticated systems using multiple narrow antenna beams. One approach was the construction of arrays of dipole or Yagi antennas with switchable phasing networks that would produce a narrow antenna beam and also allow the beam to be tilted to different directions. Important observations of the precise relationships between radio wave absorption and visual aurora have been made with such systems [e.g. Kavadas, 1961; Ansari, 1965; Berkey, 1968]. Another approach was the construction of systems that could perform simultaneous, closely spaced observations of absorption intensities. Typically, such systems would use sets of riometers with antennas pointing to different directions to enable a coarse mapping of the absorption intensities across the sky. Such systems have provided basic information about the spatial distribution and the dynamical properties of energetic particle precipitation during auroral activity (e.g. Ecklund and Hargreaves, 1968; Hargreaves, 1969; Hargreaves, 1970). A major advancement of the riometer antenna construction technique came with the development of the Butler matrix phasing system (Butler and Lowe, 1961), which combines an array of N2 (wide-beam) antenna elements such that a corresponding number of N*N discrete, narrow beams are formed. Such systems have been installed at Troms, at Ny-Alesund and at Syowa, and the observations have been used for, among others, investigations of spike
events [Hargreaves et al., 1979; Nielsen, 1980], absorption pulsations [Kikuchi et al., 1988], substorm expansion (Nielsen et al., 1988) and drift of auroral absorption pulsations [Kikuchi et al., 1990].

The riometer technique for examining electron density enhancements in the ionosphere is based on the absorption of cosmic radio noise, the broadband RF energy radiated by stellar sources in the galaxy [Little and Leinbach, 1959]. Riometer measurements are usually made at frequencies in the range of 20-50 MHz; the absorption of radio energy at these frequencies is sensitive to changes in electron density in the ionospheric D and E regions. Auroral absorption is caused by the precipitation of energetic (> 10 keV) electrons from the magnetosphere, which increases the ionospheric electron density between ∼ 70 and 120 km altitude [e.g., Rees and Luckey 1974; Christon et al., 1988].

India had its first imaging Riometer installed at the Indian Antarctic station, Maitri during Austral summer of 2009-2010. The purpose of its installation at Maitri is to understand the magnetosphere-ionosphere coupling process in terms of energetic particle precipitations due to substorm, wave-particle interactions or, Solar flares. Additionally, Maitri (L= 5; CGM 63.11 S, 53.59 E) is located at the equatorward boundary of the conventional auroral oval, which comes under the influence of auroral electrojet during enhanced geomagnetic activity. In this thesis efforts have been made to understand the changes in auroral dynamics during substorm processes of different kinds.

Chapter 1

The first chapter is introductory and briefly describes the basics of solar-terrestrial interactions and their geo-effectiveness, basic concepts such as solar wind, interplanetary magnetic field, terrestrial magnetosphere and solarwind-magnetosphere-ionosphere coupling processes, have been explained. It also describes charge particle motions in the Earth’s magnetic
field, scattering processes, wave particle interactions leading to particle precipitation. Processes such as Magnetospheric substorm, Geomagnetic storm, solar flares and magnetospheric currents also get attention in this chapter. Part of this chapter has been dedicated to describe the propagation of radio waves in an ionized medium, which forms the basic essence of the thesis.

**Chapter 2**

Cosmic noise absorption (CNA) measured by imaging Riometer, is an excellent tool to passively study the high latitude D-region ionospheric conditions and dynamics. This phased-array system of antennas experiences the trans-ionospheric cosmic noise signal level on the ground (Little, 1954; Little and Leinbach, 1958; Little and Leinbach, 1959). For the first time, a new imaging Riometer has been installed and is currently operational at Indian Antarctic station Maitri (Geographic 70.75 degree S, 11.75 degree E; corrected geomagnetic 63.11 degree S, 53.59 degree E) which is a sub-auroral station (Arun et al., 2005) since February 2010. This is the first thesis of its kind where the Indian imaging Riometer data has been used extensively. Therefore, this chapter has been dedicated to elaborate the set up of the installed imaging Riometer facility along with the importance of the location in terms of geomagnetic activities. In addition to instrumentation description, principle of CNA measurements and its applications have also been explained in this chapter. Detailed analysis of quiet day curves (QDC) clearly suggested a sidereal shift of around 2 hours between consecutive two months. It is also observed that cosmic radio noise signal exhibits seasonal dependence along with its diurnal characteristics. This suggested that changes in the ionospheric conductivity in the D-region due to solar ionisation plays a vital role in quiet time Cosmic noise signal strength. The main objective of installing the imaging Riometer at Maitri is to study magnetosphere-ionosphere coupling during substorm processes. Hence, some of the typical examples of disturbed time CNA associated with storm-time and non-storm time substorms have been discussed. Results reveal that CNA is more pronounced during storm-time substorm as compared to non-storm
time substorm. The level of CNA strongly depends upon the strength of convection electric field and the duration of south-ward turning of interplanetary magnetic field before the substorm onset.

Second part deals with the study of solar flares and their relation to D-region ionization with the help of imaging Riometer at Maitri. Solar flare is an intense transient solar phenomena mainly classified by the peak flux of soft X-ray in the 0.1-0.8 nm which is measured by GOES X-ray detector. Intensified X-ray and EUV can ionize the lower part of ionosphere leading to sudden cosmic noise absorption (SCNA), sudden increase of total electron content (SITEC) and many other activity (Donnelly, 1976; Mitra, 1974). Many studies have been done on the solar flare effect on D-region ionosphere using Riometer with different frequencies such as 18.3 MHz (Shain and Mitra, 1954) at Australia and 16 KHz (Bracewell and Straker, 1949) at England respectively. Additionally, Bhonsle and Ramanathan (1960) also showed the SCNA events with the help of Riometer of 25 MHz at Ahemadabad (23°N, 72°E). In the current study, we have used the imaging riometer of 38.2 MHz, which is almost double the frequencies used in the past solar flare studies. Three years (2010, 2011 and 2014) X-ray data from GOES sattelite have been analyzed in corroboration with riometer data for this study. No effect of any flare (X, M or, C) was seen in the riometer data. The reason for such results is attributed to the lack of thresold D-region ionisation, reduced collision frequency compared to low latitude and high opearating frequency of the riometer. Theoretical explanation based on Appleton- Hartee equation has also been provided to explain the observation.

Chapter 3

This chapter has focused on the substorm related CNA events equatorward of the auroral oval and their relation to interplanetary conditions. Cosmic noise absorption (CNA) at high latitudes is a typical manifestation of enhanced precipitation of energetic charged particles (> 20 KeV) during the course of a magnetospheric substorm (Wild et. al., 2010). In this
chapter, preliminary analysis demonstrates that energetic particles precipitate to the high latitude ionosphere during substorms, affecting upper and lower regions of the ionosphere simultaneously. Previous studies have reported that intense and short-lived CNA events associated with substorms are mostly observed in the midnight sector of the auroral oval. In the current study, it has been confirmed that such types of CNA events predominantly occurring during 0000-0600 UT (2300-0500 MLT) at an Indian Antarctic station Maitri (corrected geomagnetic (CGM) coordinates 63.110 S, 53.590 E), which is located at the equatorward edge of the auroral oval. Statistically, a profound correlation is seen (Corr. Coefficient (R)=0.86) between the substorm occurrences and the intensification of westward electrojet over Maitri during these events. However, correlation between substorm occurrences and CNA production at Maitri is relatively less (R=0.67). This suggests that not all substorm activity can alter the state of Ionosphere at Maitri. Factors like the level of substorm activity and energy of the precipitated charge particles determine the disturbances at that location. Additionally, absorption events related to isolated substorm and storm-time substorms exhibit distinct features in terms of their intensity and extent in latitude and longitude. Study also suggests that intensity of CNAs depends on the interplanetary conditions, such as, the solar wind speed, southward component of IMF Bz, and duskward component of IEF Ey. It is found that the role of duskward component of IEF Ey is more noteworthy than other interplanetary parameters for the CNA production.

Chapter 4

In this chapter, we have tried to understand the cause of day side CNA and its relation to ring current energetic electrons. The wave-particle interaction set up between the Ultra-low Frequency (ULF wave and the drifted energetic electrons at the equatorial plane causing loss cone scattering of these electrons is perceived to be the cause of such anomalous day side absorption at high latitude.
On 02 April, 2011, couple of enhanced cosmic noise absorptions (CNAs) events were observed at Maitri. Of these two events, the one which occurred earlier is due to auroral substorm onset. However, the current study is concerned about the event that occurred later during 1000-1300 MLT (MLT= UT-1, at Maitri, Antarctica). We call this CNA event as day side CNA (DCNA). Unlike Auroral substorm absorption, DCNA is not as frequent as Auroral substorm absorption events. Absence of westward electrojet at Maitri during DCNA confirms its dissimilarity from Auroral Substorm absorption events. Initially, comparison is set between the DCNA event of 02, April, 2011 and another day (14 July, 2011) with similar condition but no DCNA. The comparison has been made in the light of interplanetary conditions, imaging Riometer data, ground magnetic signatures, GOES electron flux density and associated geomagnetic pulsations. Study shows that stronger eastward interplanetary electric field favours the occurrence of DCNA event. It is concluded that DCNA events are not due to energetic particle injection along Field lines, rather it is because of gradient curvature drift of trapped non-relativistic electrons in equatorial plane. The method for Azimuthal drift calculation) is adopted from Beharrell et al, 2015 (mentioned in section 3.5). Using the formula, we calculate the energy band of trapped electrons which took part in the precipitation and the same was later confirmed with GOES particles data. The reason for precipitation of electrons is expected to be the loss cone scattering caused geomagnetic pulsation via low band chorus (LBC) wave growth.

Chapter 5

This chapter has been dedicated to study the high latitude impact, specifically at Maitri, Antarctica of the largest geomagnetic storm since the beginning of the current solar cycle (solar cycle 24). The sudden storm commencement of this severe geomagnetic storm (level G4) has been observed at 0445 UT on 17 March, 2015. The SYM-H index reached two local minima of -93 and -150 nT at 0940 and 1630 UT, respectively. The minimum of the SYM-H index of -226 nT occurred at 23 UT. The recovery period has started at 2300 UT of 17
March, 2015 and extended up to several days. We have observed extended day side CNA with no sign of westward electrojet during late morning hours to noon hours at Maitri on the 18 March, 2015. Also, we have observed simultaneous geomagnetic pulsations and pulsations in CNA in the range of Pc5 (1-7 mHz) during the day side CNA event at Maitri. Presence of global Pc5 pulsations were detected during 18 March, 2015 (first day of the recovery period of the storm) with the help of Intermagnet and IMAGE chain magnetometers. We attribute this huge day side CNA to the interaction between the Pc5 pulsations with the sub-relativistic electrons via low band chorus wave growth. The modulation of CNA is caused by local Field line oscillations at Maitri, which might be controlling the rate of diffusion. Additionally, we have used Entropy method to find out the cause and effect relationship between the geomagnetic pulsations and pulsations in the CNA. Results reveal that geomagnetic pulsations cause the modulation in CNA.

Chapter 6

The important results and findings from the studies described in the second, third, fourth and fifth chapters are summarized and scope for the future work has been discussed.

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