Chapter - 1

Dynamics of Auroral Phenomena
1.1 Introduction

The earth's atmosphere from an altitude approximately 70 to over 300 km is plasma. This natural blanket of plasma, the ionosphere has long been used to reflect radio waves back to earth. The particles of the ionosphere incidentally are ionized by radiation from the Sun. Further into the space there are zones of plasma trapped in the earth's magnetic field, the particles which are trapped in these zones are supplied by the Sun. And of course, man can be counted on to create plasma whenever it is detrimental to communication processes. Plasma is capable of doing very strange things to electromagnetic waves. One electromagnetic wave traveling through plasma may under certain circumstances interact with a second wave in such a way that the modulation or information imposed on the first wave is transferred to the second.

1.2 The Ionosphere

The upper atmosphere is ionized primarily by solar UV and X-ray radiation and at higher latitudes, and by the precipitation of energetic charged particles from the magnetosphere starlight and cosmic rays which are minor ionization sources that have some influence in the night side ionosphere. The ionization rate depends on the intensity of ionizing radiation on the atmospheric density and composition and on the ionization cross section of the atmospheric constituents. Absorption causes the intensity to decrease with decreasing altitude. The ionization production rates peak at an altitude near where the radiation has decreased to 1/e of its
intensity at the top of the atmosphere, which depend on the absorption cross section of the atmospheric constituents to the particular type of radiation (wavelength of electromagnetic radiation or and energy of precipitating particles). Except for Lyman-α radiation, which can ionize the minor constituent nitric oxide, and cosmic rays, almost all ionizing radiation is absorbed above 80 km in the atmosphere.

The ions produced are N$_2^+$, O$_2^+$, N$^+$, and O$^+$, but these are reactive with the neutral gases and the nitrogen ions are rapidly converted to NO$^+$. The dominant ions present are therefore NO$^+$, O$_2^+$ and O$^+$, with the molecular ions predominant below 150 km and O$^+$ predominant above 200 km and a mixture in between. The right side of typical distributions of the major ion species is the daytime ionosphere. Negative ions and more complex positive ions become important only below about 90 km where conductivities are relatively small. Between about 90 and 150 km the sum of the densities of NO$^+$ and O$_2^+$ is approximately equal to the electron number density. The ionization source at day, solar extreme-UV light varies significantly with the level of solar activity. The ionospheric region around the minor peak in density near 105 km is known as the E-region, while the larger density region above 150 km is known as the F-region. The E-region and lower part of the F-region undergo relatively greater variations in electron density between day and night than does the upper F-region. This is especially true during high levels of solar activity when F-region Pederson conductivities are particularly
large both because of high electron densities and high neutral densities that lead to high ion-neutral collision frequencies. Because the vertical distribution of F-region electron density is highly variable, the F-region Hall conductivity also varies in proportion to the electron density.

The high-latitude night side ionosphere displays the greatest degree of variability due to the highly variable nature of auroral precipitation. Particle precipitation can also influence the low-latitude nighttime ionosphere enough to effect the Pedersen conductance at solar minimum (Rowe and Mathews, 1973). High-latitude conductivities, although highly variable tend to be greatest in the auroral zones. Fuller-Rowell and Evans, (1987) determined the average fluxes of auroral electron precipitation as a function of magnetic latitude and magnetic local time for ten levels of hemispherically integrated energy fluxes and used these to calculate the auroral component of ionospheric conductance.

The free electrons and ions in the Earth’s ionosphere make it conducting currents flow that are connected with the magnetosphere above and to a much weaker extent with the poorly conducting atmosphere below. One of the important generators of the ionospheric current is the ionospheric wind dynamo. In the daytime ionosphere the largest current flow between 90 and 200 km, this general region is sometimes called the dynamo region. The currents and electric fields interact with the dynamics of the ionospheric plasma and neutral air in and above
the dynamo region and call the electrical phenomena. The currents in the ionosphere and above produce magnetic perturbations that can be at the ground and in space. The currents associated with the ionospheric dynamo have regular smooth daily variations. The main part of these currents is often referred to as Sq (solar quiet) or Sr (solar regular). By contrast the currents associated with solar-wind/magnetosphere interactions are highly variable when they are weak one speaks of a magnetically quiet period, and when they are strong one speaks of a magnetically disturbed period the most dramatic manifestation of which is the magnetic storm. During disturbed periods the magnetospherically produced electric fields and currents can dominate over those produced by the ionospheric wind dynamo. Ionospheric currents have been measured by rocket-borne magnetometers (Cahill, 1969; Shuman, 1970; Yabuzaki and Ogawa, 1974; Burrows and Sastry, 1976; Burrows et al., 1977; Sampath and Sastry, 1979) and by incoherent scatter radars (Harper, 1977). The typical vertical profiles of current density are calculated from radar measurements of electron density, electric field and ion velocity. At other times and locations the vertical distribution of current can be quite different reflecting the influence of winds that vary in height and time as a collection of current profiles obtained from rocket-borne magnetometers near the magnetic equator off the coast of South America showing the equatorial electrojet. The magnetic effects of meridian currents in the equatorial ionosphere

The geomagnetic perturbations are caused both by variable magnetospheric activity and by changes in the winds and conductivities in the dynamo region. The auroral electrojets are the most prominent manifestation of the variability in magnetospheric activity. These are connected by geomagnetic-field-aligned currents with the outer magnetospheric. The field-aligned currents along with magnetospheric ring currents and currents at the magnetopause and in the magneto tail contribute to ground-level magnetic perturbations seen at middle and low latitudes and are responsible for the fact that disturbance magnetic perturbations occur even at night in the absence of significant ionosphere conductivity.

1.3 The Magnetosphere

The name magnetosphere is assigned to the region in which because of the lightness of the ions the diminution in the gravitational field and the long free paths the motions of the particles are primarily controlled by the Earth's magnetic field. This statement itself implies that the particles are (mainly) charged a result which comes about because the ambipolar field doubles the scale height for the charged components Magnetic fields around our planet act as an obstacle and prevent the solar wind from reaching our earth. The solar wind streams outward from the sun towards the earth and decelerated at the bow shock in front of the magnetopause before it flows through the magnetoseath Fig. 1.1.
Fig. 1.1 The earth's magnetosphere and the main current systems
In a pure vacuum devoid of any other matter or magnetic fields a charged particle such as an electron or a proton will emit light only if it is accelerated. Acceleration is defined as a process by which there occurs a change in velocity over a unit time. It has been known for some times that charged particles spiraling in magnetic fields will give off electromagnetic waves. The frequency of the emitted waves is usually related to the strength of the magnetic field. This process and others like it are responsible for the generation of a whole host of electromagnetic and electrostatic waves in the Earth’s magnetosphere.

Some of these waves are trapped within the magnetospheric, such as ion cyclotron and electron whistlers, ELF and VLF hiss, and chorus just to name a few. Other magnetospheric electromagnetic waves can travel to great distances such as the non-thermal continuum radiation and auroral kilometric radiation. They can easily be observed in interplanetary space. The magnetosphere is a complex configuration of plasma regions, particles, and electric currents. In reality, regional boundaries are not as well defined as implied above since the magnetosphere is a dynamic, fluctuating system. Though we do not yet fully understand many of the physical mechanisms and processes that drive the magnetosphere, we do know that the space around Earth is a highly responsive buffer zone against the high speed solar wind. Invisibly, sometimes violently, the magnetosphere reacts to events on the Sun as they are communicated through the Earth’s magnetosphere by the solar wind.
The nightside magnetosphere stretches away from the sun behind the earth and is called the geomagnetic tail. The region of the magnetosphere is important because it acts as a reservoir of energy. The current sheet lines in the center of the tail embedded within two regions characterized by hot particle populations are called the plasma sheet. The north and south tail lobes lay on both sides of the plasma sheet and connect magnetically to the two polar region of the earth. The first region is characterized by very energetic ions and electrons and is called the Van Allen radiation belts. The particles in the radiation belts are trapped and circle the earth from about 1000 km above the surface to a geocentric distance of about 6Re, and another major particle population the ring current particles. "Ring current particles" refers to those components of the particles distribution that contribute most to the total current density. The third major particles population in this region is a dense cold particle population in the so-called plasma sphere which coexists in almost the same region as the radiation belts. The plasmasphere is tourus-shaped and extends to 3-6 Re from earth at the equator.

Solar energetic particles (SEPs) are electrons or heavy ions that are accelerated due to solar activity. Solar flares and interplanetary shocks associated with coronal mass ejections (CMEs) are the most important sources of these particles. SEP ions can be a major source of energetic particles for the Earth’s magnetosphere. We know several ways energetic ions can reach magnetospheric field lines. To understand the entry of these ions into the magnetosphere and to
model it, more quantitatively, we need more detailed calculations of SEP entry and transport in realistic models of the magnetosphere and its interaction with the solar wind. One approach to quantifying ion entry and identify its mechanisms is to follow a large number of test ions in magnetic and electric field models of the magnetosphere.

The layer separating the ionized magnetosphere and the neutral atmosphere is called the ionosphere and extends from approximately 80 km and up to about 1000 km. Both photons from solar radiation and precipitating energetic particles ionize the neutral gas in the upper atmosphere. Particles can be trapped at closed magnetic field lines and the magnetic mirror force will make electrons bounce back and forth accelerated by magnetic field–aligned electric fields to such high energies that some of them will overcome the mirror force and penetrate into the ionosphere.

The line of the geomagnetic field is frozen into the ionospheric-magnetospheric plasma. The motion of the plasma and the field on the other hand the trapped radiation is so much less significant that in spite of the great energy of the particles they do not significantly disturb the field as a whole as is evidenced by the fact that geomagnetic storm variations of the mean value.

The ionosphere, a region of variable height that is populated by charged particles. Some of the cold ionospheric electrons and ions evaporate from this area into the plasmasphere, a region of dense, cold, low-energy plasma. Both the
plasmasphere and the ionosphere shift in size and density in response to disturbances elsewhere in the magnetosphere.

1.4 Magnetosphere-Ionosphere Coupling

The solar terrestrial interaction regarding the magnetosphere - ionosphere dynamics is the aurora borealis observed at high latitudes in the northern hemisphere and their counterpart the aurora australis observed in the southern hemisphere. These dynamic displays of the multicolored luminosity have fastigiated and puzzled natural scientists down through ages. However it was only towards the end of the nineteenth century that our scientific understanding of the phenomenon was put on affirm basis. By the early 1920’s certain facts were clear. The aurora was associated with an electrical discharge phenomenon and luminosity was due to the excitation of atmosphere. Infact the great Norwegian physicist Kristian Birekland, realized that the electrons which bombarded the ionosphere could also carry the current which it was realized must flow in the region in and above to infer the physical process which directly led to the aurora.

It is likely that active auroras associated with substorms are a primary work of the magnetosphere. Diffuse auroras which usually appear in post breakup times may be considered to be the work of the magnetosphere since they are thought to result from strong pitch angle diffusion of energized particles in the magnetosphere disturbed by substorm activities. Quiet auroral arcs on the other hand appear and move in a gentle manner. Judging from the gentle movement
ascrivable to the ExB drift it is seen not unlikely that they are able to be explained by some feedback mechanism between the ionosphere and the magnetosphere.

The near-earth space environment, the magnetosphere, is loaded with energy from the interaction with the highly variable solar wind. Part of this energy is in turn dissipated by particle precipitation into the ionosphere, giving auroral display. The auroras are therefore the most fascinating manifestation of the energy coupling between the solar wind and magnetosphere–ionosphere system.

1.5 Aurora Formation

Aurora borealis (northern lights) is a magnificent celestial phenomenon that reveals itself in the polar regions against a star-spangled firmament. These northern lights have left their marks in our culture in several different ways. Many have been inspired and by this mysterious veil of colour. Norwegian scientists have made significant contributions to the scientific investigation of the aurora. At the turn of century professor Kristian Birkeland (1867-1917) presented the first realistic theory of the northern light. He supported his theory with laboratory. New discovery about the auroral observatory. New discoveries about the aurora were provided by professors Carl Stormier and Lars Regard, based on the new, important techniques in auroral research which they introduced. The basic information about the aurora has been obtained during the space age.

The earliest recollection of the aurora borealis, the northern lights, is from a song of the 1950s called "the Northern Lights of Old Aberdeen", which I always
took to be a reference not to Scottish traffic arrangements but to the celestial phenomenon of bands, curtains or streamers of colored light that appear in the sky predominantly in the Arctic and Antarctic regions of the earth. In the Antarctic, the lights are called the Aurora Australia, or Southern Lights. They are visible, though less frequently, also outside those zones.

The differences between dayside and nightside auroras versus altitude of ground and satellite observations have shown that northern lights occur most frequently within continuous oval-shaped zones centered at the Earth's magnetic poles. The dayside aurora is located ~8-10 degree (~100km) closer to the pole than the nightside aurora. Sealboard is the most easily accessible area in the northern hemisphere, where the dayside aurora can be observed from the ground.

The aurora is the most readily observed consequence of the dynamic magnetosphere and the most obvious characteristic of the high-latitude ionosphere. Mankind must have been looking at the northern and southern light in the night sky, the aurora borealis and the aurora australis, for thousands of years, which surely puts them amongst the oldest known geophysical phenomena, though it is only in the last part of the 20th century that any proper explanation has become possible. The term aurora borealis dates from 1621. There are detailed reports of auroral displays dating from 1716 and the first written work devoted entirely to the polar aurora was published in France in 1733, but accounts of light in the night
sky, which were frequently given a mystical or prophetic interpretation, go back to Greek and Roman times.

Early 'theories' range from the fanciful to some that were unwittingly near the truth: sunlight reflected from the polar snow and ice (wrong), 'elastic fluids' (vague), electric discharges (plausible). Only in the early 1950s was it proved that the immediate cause of the auroral emissions is excitation of atmospheric gas by energetic particles and it was not until 1958, when rockets were fired into an aurora, that energetic electrons were identified as the primary source. An understanding of the source of physics of the magnetosphere. In fact that knowledge is not yet complete, though current ideas are well advanced and stand on firm ground.

The aurora comprises a group of upper-atmosphere phenomena, not only the emission of light. Each is a direct or an indirect consequence of the entry of energetic particles from the magnetosphere to the atmosphere.

The aurora phenomena have several features in common. They are all related to solar activity in a general way, though usually without specific association with any particular solar event. The term region was used from the 1930s to denote an unseen solar region causing aurora and magnetic storms, and for 40 years it served as a unifying hypothesis. It is now understood, of course, that the connection from the sun is via the solar wind.
In general the auroral phenomena are highly structured in both space and time, with occurrence patterns that are essentially zonal. The classical picture of aurora occurrence (Figure 1.2) shows 100% occurrence at the peak of a zone centered between geomagnetic latitudes 65° and 70°, with the occurrence rate falling off on both the equatorward and the poleward sides. But in 1963, Y.I. Feldstein, analyzing data from the International Geophysical Year (1957-58), pointed out that the locus of the aurora at a fixed time is not circular but oval (Figure 1.3). The maximum is near 67° at midnight, increasing to about 77° at noon, and the classical zone is the locus of the midnight sector of the oval as the Earth rotates underneath it. To a first approximation the oval is fixed with respect to the Sun. The auroral oval is of the important boundaries of geospace. In relation to the structure of the magnetosphere it is generally considered to mark the division between open and closed field-lines.

The auroral acceleration region provides an easily accessible region where plasma acceleration processes of solar and cosmic importance can be studied. In addition the auroral acceleration region plays an important role in the magnetosphere. The basic features were discovered by a succession satellite, including ISIS, S3-3, Dynamics Explorer, Viking, and Akebono. Those spacecraft identified the essential properties of inverted-V electron beam electrostatic shocks, ion beam and conics, density cavities and numerous wave mode including auroral kilometric radiation ion cyclotron waves and VLF auroral his and saucers. The
Fig. 1.2  The Sky Aurora [Newell et al 1996]
Fig. 1.3 Natural Auroral Formation [Newell et al 1996]
Freja satellite, launched in 1992, carried out auroral investigations with temporal and spatial resolution similar to that of rockets, at altitudes as high as 1750 km. (Lundin et al., 1998). The FAST emission was designed to make similar high time resolution microphysics measurements of higher altitudes within the auroral acceleration region. Intense ion cyclotron waves are generated within these “inverted-V” electron regions. Cattell, et al., 1998, and Chaston, et al., 1998 show that the pointing flux carried by these waves can be as large as 10% of the associated electron energy flux. Direct measurements of electron modulations caused by ion cyclotron waves (McFadden, et al., 1998a) confirm the model suggested by Temerin, et al., 1986 that this process is responsible for modulation electrons that create flickering aurora observations of preferential heating of He⁺ conics associated with ion cyclotron waves (Lund, et al., 1998).

Auroral acceleration region accelerates electrons both upward and downward along magnetic field lines though the downward acceleration dominates and is of course better known because it creates the visible aurora. Ions on the other hand with a few but interesting exceptions are mostly accelerated upward. Ions that do precipitate into the atmosphere are due predominately to the direct injection of ions into the loss cone in region above what I here consider the auroral acceleration region. Ions precipitate into the ionosphere in the cusp by direct entry from the magnetosheath due to reconnection or by pitch angle scattering from the ring current. The average properties of precipitating electrons
has been well established in several studies by Newell, et al., 1996 on the basis of
data from the DMSP satellite. The average properties of up going ions as seen by
the DE-1 satellite were described by Yau, et al., 1985. Upgoing electrons seen
near the equator have been described by Klumpar, 1993.

Though auroral acceleration processes occur to some extent along the whole
field line, measurements from S3-3, Viking and DE satellites have established that
a large portion of the particle acceleration that occurs on auroral field lines occurs
in an altitude range of about 1000 km to about 10000 km. The simple explanation
for this is that it is in this region that the relative drift velocities between ions and
electrons are maximum since the field-aligned currents increase in proportion to
the magnetic field but the plasma density is still small.

1.6 Ion Cyclotron waves (ICWs)

The velocity of a particle can be divided into parallel motion along the
magnetic field and perpendicular motion, which is a nearly circular motion around
a magnetic field line with a frequency given by the gyro frequency (gradient and
curvature drift are typically small and the ExB drift can be removed by moving
into the ExB reference frame). Averaging over a few gyro periods then gives the
result that the important electric field from the point of view of particle
energization are the parallel electric fields and those perpendicular wave fields that
have a frequency of the gyrofrequency. Further averaging over a few wave periods
gives the result that the important wave electric fields are those that have a parallel
phase velocity equal to the particle phase velocity (Landau resonance). Waves near the fundamental and the lowest harmonics of the proton cyclotron frequency have been reported from spacecraft observations on S3-3 (Kintner, et al., 1978, 1979), ISIS 2 (Yoshino, 1991), Viking (Andre, et al., 1987), and ISEE (Cattell, et al., 1991). They occurred on auroral field lines in a wide range of altitudes from below 0.5 $R_E$ (Earth radii) up to more than 3 $R_E$. The main feature of the wave spectra is the principal peak near the local proton cyclotron frequency; it is often accompanied by peaks at a few (typically one or two) higher harmonics. These waves have often been labeled as electrostatic, though direct measurements showing the wave magnetic field to be negligible were not often made. Kintner, 1980 described two distinct types of ion cyclotron phenomena.

The occurrence and properties of ICWs in region of auroral electron acceleration has been well documented with observations of electric and magnetic field oscillations with frequencies in the vicinity of $\Omega_i$ from OV1-10 (Heppner, 1969), Injun-5 (Gurnett, and Frank, 1972), DE-1 (Gurnett, et al, 1984), S3-3 (Temerin and Lysak, 1984), ISIS-1-2 (Saito, et al, 1987), Viking (Gustaffson, et al., 1990), ISEE (Cattell, et al, 1991) and Freja (Erlandson, et al, 1994) and from auroral sounding rockets (Lund, et al., 1995, 1997).

At the present time there is a considerable interest in ion-cyclotron resonance heating because this process is among the most promising ones for achieving an efficient heating by the ion-cyclotron resonant method. Ion cyclotron waves were
observed by the magnetic field experiment on board ATS 6 [Fraser, 1982] and on board GEOS 1 and 2 (Korth, et al., 1984). These include fast and oblique propagation of ion-cyclotron waves (Leamon, et al., 2000; Holl-weg 2000), the need to develop a kinetic treatment (Isenberg, et al., 2001), fast shocks heating (Tu and Marsch, 2001; Lee, 2001), turbulence-driven ion-cyclotron waves (Li, et al., 1999), and others. Nevertheless, there seems to be some observational evidence that parallel propagating ion-cyclotron waves are at the origin of ion heating and acceleration (Tu and Marsch, 2001; Isenberg, et al., 2001). Observations of heating and acceleration of heavy ions in the solar corona by SOHO, have shown very large thermal anisotropy for O\textsuperscript{+5} ions with values ranging between $10 < T_\perp /T_\parallel < 100$ (Kohl, et al., 1998, Li, et al., 1998; Cranmer, et al., 1999a, 1999b). In a chapter (Marsch and Tu, 2001) suggested that the heavy ion drift velocity relative to the protons, and large thermal anisotropy could trigger a cascade of ion-cyclotron waves too much higher frequencies.

1.7 Electrostatic Ion Cyclotron Waves (EICWs)

The electrostatic ion cyclotron waves (EIC) were first discovered in 1961 by D’Angelo and Motley, Drummond and Rosenbluth 1962 qualitatively explained the experimental results of D’Angelo and Motley 1962 using kinetic theory. The broadly accepted picture of electrostatic ion cyclotron instability (EICI), in accordance with the kinetic Drummond-Rosenbluth theory, until the end
of the seventies was the resonant convective instability destabilized by the plasma electrons. Sato, et al., 1985 suggested that the EICI is two-dimensional potential relation instability. Kindel and Kennel 1971 compared the criteria for the excitation of the EICI to the excitation of current-driven ion acoustic waves or the Buneman instability.

Electrostatic ion cyclotron (EIC) waves have been observed on auroral field lines by many satellites including S3-3 (Kintner, et al., 1978, 1979; Temerin, et al., 1979), ISEE-1 (Cattell, et al., 1991), Viking (Andre, et al., 1987) and Polar (Mozer, et al., 1997). The waves are usually associated both with field-aligned currents and up flowing ion beams (Kintner, et al., 1979; Cattell, 1981; Cattell, et al., 1991). Currents, ion beams, and velocity shear have all been proposed to provide the free energy for the instability (Kindel and Kennel, 1971; Hauck, et al., 1978; Bergmann, 1984; Ganguli, et al., 1988). In addition, some studies suggest that the observed electrostatic waves near the various ion gyro frequencies may be due to relative streaming between ion species (Bergmann, et al., 1988; Kaufmann, et al., 1986; Dusenbury, et al., 1988). Although these waves have been extensively studied, the resolution of the data and lack of information on the background electron density and temperature have not allowed the definitive identification of the free energy source for the waves.
We describe observations of waves near the cyclotron frequencies of H\(^+\), O\(^+\), and He\(^+\) and the associated particle distribution functions and field-aligned currents during one night side aurora zone crossing by the FAST satellite (Carlson, et al., 1998a). An overview of 3 minutes of data are obtained as FAST moved pole ward through the aurora zone and into the polar cap at an altitude of \(\sim 3800\) to 4000 km near midnight magnetic local time on January 13, 1997 at 10:15. The electron pitch angle and energy spectra are plotted in panels a and b, and the ion spectra in panels c and d show the Fig. (1.4). Two regions of ion beams occurred (see peaks in the pitch angle spectrum at 180 in panel d). The beam composition was variable, including a large fraction of both O\(^+\) and He\(^+\). There were also many regions of intense up flowing electron beams (panel b; see Carlson, et al., 1998b). The signatures of three field-aligned current sheets can be seen in the eastward component of the magnetic field (panel e). The most equator ward (during the first ion beam) is upward, followed by a downward current sheet (with smaller scale embedded upward currents) during the interval of upward electrons, and, finally, a small scale upward current at the pole ward edge of the aurora zone. The current densities were \(\sim 2-4 \times 10^{-7}\) A/m\(^2\), assuming that the observed change in the field was primarily due to the motion of the satellite rather than the motion of the
Figure 1.4 An overview of 3.5 minutes of data at 23.8 MLT in the auroral zone. (a) Electron energy spectrum; (b) Electron pitch angle spectrum; (c) Ion energy spectrum; (d) Ion pitch angle spectrum; (e) eastward and northward components of the magnetic field in field-aligned coordinates; and (f) Power spectrum of the electric field along the satellite velocity vector (~ perpendicular to the magnetic field). The hydrogen cyclotron frequency is the white line [Carlson et al, 1998].
current sheets. The power in the electric field component along the spacecraft velocity vector, approximately perpendicular to the geomagnetic field, (panel f) indicates that there were several bursts of waves (~10:17:40 and ~10:19:20) near the H⁺ cyclotron frequency (f_{cH} \sim 205 \text{ Hz}), the He⁺ cyclotron frequency (f_{cHe} \sim 51\text{Hz}), the oxygen cyclotron frequency (f_{co} \sim 13 \text{ Hz}) and their harmonics. The rest of the emissions were less structured, showing either very broadband or low frequency waves. The waves and distributions are examined in detail during four intervals: (1) 10:16:34, during the long duration ion beam and down going electron inverted V; (2) 10:17:37-10:17:41, during an intense up flowing electron beam with a clear beam; (3) 10:19:05, during a more typical upward electron event which also had counter streaming; and (4) 10:19:17 -10:19:22, during the ion beam near the polar cap boundary.

The waveform in panel a, obtained during interval 1, is non-sinusoidal with a characteristic frequency of \sim 45 -50 \text{ Hz} and an amplitude of \sim 200 \text{ mV/m}. Somewhat later, waveforms have, in addition, large amplitude variations near f_{ci}. Panel b (interval 2) shows another example of a non-sinusoidal waveform with a characteristic frequency near f_{cH} with a longer modulation near 10 \text{ Hz}. Very nonlinear spike lets are often observed in similar up flowing electron regions (Ergun, et al., 1998). The waveform during interval 3 (panel c) does not exhibit very clear frequency structure. The waveforms observed during interval 4 (panel
d) are quite variable. At times, the waves are very coherent and sinusoidal; at other

times, there are multiple frequencies and/or non-sinusoidal shapes.

1.8 Electromagnetic Ion Cyclotron Waves (EMICWs)

The first mathematical treatment of electromagnetic ion cyclotron (EMIC) wave
generation in a proton-electron plasma were made by Cornwall (1965) and
Kennel and Petschek, (1966). These plasma waves are transverse, left-hand
circularly polarized (LCP) waves with frequencies below the equatorial proton
gyrofrequency, $F (H^+)$, at which point a resonance occurs. These waves can travel
from the equatorial source region to the ionosphere along the magnetic field lines.

The polarization of the 0.1 Hz polar signals between 1300 and 1400 UT,
given in the third panel of the ULF bursts between 1338 and 1345 UT clearly have
elasticity near 1 or are left-handed waves (ref). The bottom panel gives the
elasticity of the ground signals showing generally a mixture of polarization with a
suggestion of right polarization ahead of 1330 UT. Such a mixture of ground ULF
waves is not unexpected since ground sensors could detect leakage of both Alfvén
and fast waves out of the ionospheric duct. The generation of electromagnetic ion
cyclotron (EMIC) waves by energetic ions in the inner magnetosphere near the
plasmapause has been analysis in various papers (Thorne and Horne, 1994;
particle populations to see whether the instability theory driven by proton temper-
nature anisotropy at geosynchronous orbit (Gary, et al., 1994; Gary, et al., 1995)
and near the magnetopause can also characterize the source of the ULF waves measured by the polar magnetometer for this event at $L = 7.5$.

The energy for the magnetosphere electromagnetic ion cyclotron (EMIC) waves comes from the anisotropic energetic (10-a few 100 keV, ring current and plasma sheet type) protons, for which $T_{\perp}/T_{\parallel} > 1$. The parameter $T_{\perp}/T_{\parallel} - 1$ is called the thermal anisotropy of a particle species with a bi-Maxwellian distribution function. Energy can be transferred from the particles to the waves when the particle gyro frequency matches the Doppler shifted wave frequency. The effective amplification of electromagnetic ion cyclotron (EMIC) waves depends on the amount of time spent propagating through a finite growth region (Kozyra, et al., 1984). Hence a convective growth rate of the instability is used instead of the temporal one; it is calculated by dividing the temporal growth rate by the group velocity of the waves. Observations have shown that the simple, one ion theory for electromagnetic ion cyclotron (EMIC) waves is not enough, as both cold and hot heavy ions are present in the magnetosphere, $\text{He}^+$ and $\text{O}^+$ being the most important. The heavy ions in the cold plasma can have profound effects on the generation and propagation of electromagnetic ion cyclotron (EMIC) waves (Young, et al., 1981; Gomberoff and Neira, 1983). The most notable new feature is the formation of stop bands above the heavy ion gyrofrequencies. The electromagnetic ion cyclotron (EMIC) waves generated inside the magnetosphere
are in the 0.1-5Hz frequency range, and are called Pc1-2 pulsations when seen on the ground.

Electromagnetic ion cyclotron instability incorporating the details of charged particles trajectory has been discussed. The wave is assumed to propagate along the ambient magnetic field in anisotropic plasma. Anisotropy in the velocity distribution of a fluid or plasma is a no thermal property, small-scale processes in such media act to reduce, if not fully thermalize such properties. In fluid or dense cool plasma the primary isotropization mechanisms are the particle–particle interactions of coulomb collisions. These collisions act at any value of the parameter characterizing the anisotropy implying that a spatially homogeneous system. The plasma is considered to consist of resonant and non-resonant particles. Here it is assumed that resonant particles participate in energy exchange with the wave whereas the non-resonant particles support the oscillatory motion of the wave. The electromagnetic ion cyclotron anisotropy instability is the fastest growing mode in an electron-proton plasma (Gary, et al., 2000). Ring current ion distributions are often unstable and can generate different classes of plasma in the equatorial magnetosphere like magneto sonic, electromagnetic ion cyclotron (EMIC) wave’s etc. The subsequent interaction of an energetic particle with a plasma wave results in pitch angle scattering and energy exchange between the particle and the wave. Scattering of ring current particles into the loss cone due to resonant interactions with EMIC waves occurs on short timescales and could
contribute significantly to ion loss (Cornwell, et al, 1970, Lyons and Thorne, 1972) especially during the main phase of the storm when ring current energy loss timescale may be as low as 0.5-1 hours. The plasma waves can also transfer energy from ring current H\(^+\) to O\(^+\) during magnetic storms (Thorne and Horne, 1994, 1997) and play an important role in the heating of the thermal electrons and ions (Cornwell, et al, 1971a, Gendrin and Roux, 1980, Thorne and Horne, 1992, Horne and Thorne, 1997).

The model suggested that these potential fluctuations propagate as electromagnetic ion cyclotron waves. Such waves have a small but finite parallel electric field component and an increased velocity as they propagate towards the ionosphere which allows them to resonantly accelerate low energy ionospheric electrons to keV energies. The one problem with the model was that the required wave amplitude was larger than had been observed. The inferred waves should have perpendicular amplitude of a few hundred mV/m. Now such waves have been observed in data from the EFI instrument on polar. The frequency is slightly below the local H\(^+\) gyrofrequency. Additional waves can be seen at frequencies that correspond to the He\(^+\) and O\(^+\) frequency. In my opinion such waves are not due to instability in the electron beam distribution but rather they are due to an oscillation of the potential structure.
1.9 Observational Evidence of EMIC Waves

The left-hand polarized electromagnetic ion cyclotron (EMIC) waves predominantly occurred in the dusk bulge region in association with increasing thermal He\(^+\) populations and anisotropic pitch angle distributions of ring current ions of energies greater than 20 keV. Observations by the active magnetospheric particles Tracer Explorers/CCE(AMPTE/CCE) Spacecraft showed maximum occurrence (10-20\%) of EMIC(Pc1) waves with left-hand polarization near the equator between 1000 and 1800 magnetic local time (MLT) at large L\(>7\) (Anderson, et al., 1992).

The predominant high-latitude (L = 6–8) ground ULF signal near local noon is quasi-structured hydro magnetic chorus/emissions (Anderson, et al., 1995). Since the early 1960s, it has been noted that the ULF waves on the ground near local noon were either turned on or enhanced in association with sudden impulses in the Earth's magnetic field (Heacock and Hessler, 1965). Early in situ solar wind measurements have related these sudden magnetic impulses with pressure pulses in the solar wind plasma which would compress the magnetosphere and could drive the trapped proton radiation unstable to electromagnetic ion cyclotron (EMIC) wave. The particle and field data from the AMPTE/CCE satellite in the outer, dayside, equatorial magnetosphere during magnetospherical compressions indeed suggest that enhancements in dynamic pressure drive the energetic proton distributions trapped in the outer magnetosphere to instability producing the
electromagnetic ion cyclotron (EMIC) waves measured by the spacecraft (Anderson and Hamilton, 1993).

The transverse ion heating also is the consequence of electromagnetic ion cyclotron (EMIC) waves. To explain the data are taken from a pass near 22 MLT as discussed by Lund, et al., (2000). This pass was geomagnetically quiet (kp = 1-). The VLF portion of the wave spectrum shows evidence of particularly low plasma density on this pass (Strangeway, et al., 1998). The ion conic event occurs at 06:44:44-58, between two ion beams, many of the electromagnetic ion cyclotron (EMIC) conics occur at the edge of an ion beam. The electromagnetic ion cyclotron (EMIC) waves occur in the presence of secondary electrons, which are the leading candidate for generating the waves (Lund and LaBelle, 1997). The characteristic energies at 06:44:52 are 1000 eV for H_e^+, 531 eV for O^+, and 86.2 eV for H^+. This ordering of energies is typical of electromagnetic ion cyclotron (EMIC) ion conics.

The distribution of events in latitude and magnetic local time is shown (Lund, et al., 2000). Electromagnetic ion cyclotron (EMIC) conics occur primarily in the pre-midnight sector. The electromagnetic ion cyclotron (EMIC) conics are most common in the pre-midnight sector and rarely found near dawn. This distribution is consistent with the magnetic local time distribution that has been observed for electromagnetic ion cyclotron (EMIC) waves alone (Saito, et al., 1987; Erlandson and Zanetti, 1998). An altitude profile is consistent with the result of Miyake, et
al., 1996 that continuous heating up to at least 10,000 km is necessary to account for the observed cone angles in ion conic distributions. The altitude distribution of our electromagnetic ion cyclotron (EMIC) events has a local minimum just above 2000 km. This altitude distribution differs some watt from the distribution of electromagnetic ion cyclotron (EMIC) waves reported by Saito, et al., 1987, which peaks below 2000 km and continues to decline at higher altitude. This discrepancy may be due to the over-representation of the pre-midnight sector, where electromagnetic ion cyclotron (EMIC) such on occurrence is highest among our high altitude samples and the lack of available passes at 1000-2000 km in this local time sector.

Fig. (1.5) by shows as the FAST burst mode data for fields and particles recorded on orbit 2653 (Cattell, et al., 1998). At this time FAST was outbound through the southern dayside aurora oval in the post-noon sector. The electric field data presented in the top panel illustrates the electric field perpendicular to $B_0$ and pointing approximately equator ward. The observed wave activity is coincident with the ion beam and enhanced down going electron beam fluxes with energies extending up to 1 keV for both species consistent with previous observations of electrostatic ion cyclotron waves and as modeled by Cattell, et al., 1998.
Fig. 1.5 The FAST burst mode data for fields and particles recorded on orbit 2653 [Cattell et al 1998].
1.10 Alfven Waves

The Alfven wave is dominant low frequency transverse mode of magnetized plasma, which propagates along the magnetic field and displays a continuous spectrum even in bounded plasma. Alfven wave named after the Swedish space physicist H. Alfven is one of the most important waves in magnetized plasma. Alfven waves in a plasma were first generated and detected by Alfven Baker, Pyle and Wilcox at Berkely, California and by Jephcott in England in 1959 during the “slow pinch “ discharge in a hydrogen plasma between two electrodes aligned along a magnetic field. This wave may play an important role in energy transport, in driving field-aligned currents in particle acceleration and heating and in explaining inverted-V structures in magnetosphere-ionosphere coupling.

Intense, transversely localized fields are frequently measured on polar-orbiting satellites (e.g., Kletzing et al., 1983; Dubinin et al., 1985; Chmyrev et al., 1988; Weimer and Gurnett, 1993; Marklund et al., 1994; Mishin and Forsfer, 1995; Aikio et al., 1995; Karlsson and Marlund, 1996) and rockets (e.g., Boehm et al., 1990) and are thought to be the lower magnetospheric signatures of auroral arcs and black auroras. Because the periods of ULF Alfven waves are compatible with fundamental field line oscillations and the time scale of particle bounce motion along auroral field lines, Alfven waves are considered as powerful agent to explain various observed phenomena in magnetosphere-ionosphere coupling (e.g., Streltsov et al., 1998). The Alfven wave connection to suprathermal electron
bursts of a few 100 eve has recently been observed by the Freja satellite (e.g., Knudsen et al., 1998; Wahlund et al., 1998) as well as the FAST satellite (e.g., Chaston et al., 1999). These work describe high field-aligned electron bursts in a broad energy range from thermal (1 eV) unto a couple of keV and strong electromagnetic spikes reaching electric fields $\sim$100 to $\sim$200 mV/m and magnetic fields $\sim$30 to $\sim$50 not associated with inertial Alfvén waves. With regards to models an important Alfvén wave model has been described in a number of works (e.g., Seyler et al., 1995; Seyler and Wahlund, 1996; Clark and Seyler, 1999). The ionosphere-magnetosphere coupling mediated by standing Alfvén waves have also been treated theoretically (e.g., Lysak, 1991; Trakhtengertz and Feldstein, 1984; Streltsov and Lotko, 1999). Thus is the present investigation we have considered some aspects of Alfvén wave also with regard to the explanation of magnetosphere-ionosphere coupling. The study an Alfvén wave has been considered as the appendix of the thesis.

1.11 Particle Aspect Analysis

The study of plasma instabilities employs either the fluid theory or the kinetic theory. The fluid theory offers the advantage of relative mathematical simplicity but is limited to relatively long wavelength plasma phenomena. The kinetic theory is mathematically more complex but describes properly the plasma instabilities with wavelength of the order of or shorter than an ion gyro radius. The kinetic theory is, in principle, more accurate than the fluid theory, although in
some circumstances it may lead to an unsolvable mathematical problem. Sometimes a less accurate model will do and in some limiting cases the fluid theory is even exact. However, in tenuous or high temperature plasmas where collisions between the constituent charged particles are rare an understanding of the plasma phenomena requires knowledge of the individual particle trajectories in the self consist electromagnetic fields. A better understanding of particle orbits in the presence of wave may be important for predicting plasma confinement, high energy particle loss, heating efficiency and current flow in the presence of wave.

The investigation of charged particle trajectories in the presence of wave paves the way to study the excitation of waves, their dispersion relations, current driven by the waves and the transfer of energy to the particles and hence heating and acceleration of the charged particles by the wave, in the same sequence of analysis, which is referred to as the particle aspect analysis.

The electromagnetic ion-cyclotron instability, incorporating the details of charged-particle trajectories, has been discussed. The wave is assumed to propagate along the ambient magnetic field in anisotropic plasma. The plasma is considered to consist of resonant and non-resonant particles. It is assumed that resonant particles participate in energy exchange with the wave, whereas the non-resonant particles support the oscillatory motion of the wave.
1.12 Summary

In this introductory chapter I have presented the general outlines of the study undertaken in the subsequent chapters. The regions of space that is ionosphere and the magnetosphere are briefly described. The recent fascinating branch of magnetosphere-ionosphere coupling and the aurora formation which have been a substorm phenomena is discussed. The brief descriptions of ion cyclotron waves are given. The two types of ion-cyclotron waves that is the electrostatic and the electromagnetic which are observed in the ionosphere and the magnetosphere are described. The observational evidence of electromagnetic ion-cyclotron waves is given which forms the basis for the subsequent chapters. The methodology of particle aspect analysis which has been adopted as the theoretical background and its importance are given. The brief description of Alfvén wave is presented which has been included as the appendix part of the thesis.