Effects of Dust particles on magnetosphere-ionosphere coupling
1.1 Introduction of Dusty Plasma:

Two omnipresent ingredients of the Universe are plasmas and charged dust. The interplay between these two has opened up a new and fascinating research area, that of dusty plasmas, which are ubiquitous in different parts of our solar system, namely planetary rings, circumsolar dust rings, the interplanetary medium, cometary comae and tails, as well as in interstellar molecular clouds, etc. (Fig:1.1&1.2). Dusty plasmas also occur in noctilucent clouds in the arctic troposphere and mesosphere cloud-to-ground lightening in thunderstorms containing smoke-contaminated air over the earth, in the flame of a humble candle, as well as in microelectronic processing devices, in low-temperature laboratory discharges, and in tokamaks. Dusty plasma physics has appeared as one of the most rapidly growing fields of science, besides the field of the Bose-Einstein condensate, as demonstrated by the number of published papers in scientific journals and conference proceedings. In fact, it is a truly interdisciplinary science because it has many potential applications in astrophysics (viz. in understanding the formation of dust clusters and structures, instabilities of interstellar molecular clouds and star formation, (Fig:1.3) decoupling of magnetic fields from plasmas, etc.) as well as in the planetary magnetospheres of our solar system [viz. Saturn (particularly, the physics of spokes and braids, the B and F rings), Jupiter, Uranus, Neptune, and Mars] and in strongly coupled laboratory dusty plasmas. Since a dusty plasma system involves the charging and dynamics of massive charged dust grains,
it can be characterized as a complex plasma system providing new physics insights. In this chapter, the basic physics of dusty plasmas as well as numerous collective processes are discussed. The focus will be on theoretical and experimental observations of charging processes, waves and instabilities, associated forces, the dynamics of rotating and elongated dust grains, and some nonlinear structures (such as dust ion-acoustic shocks, Mach cones, dust voids, vortices, etc). The latter are typical in astrophysical settings and in several laboratory experiments. It appears that collective processes in a complex dusty plasma would have excellent future perspectives in the twenty-first century, because they have not only potential applications in interplanetary space environments, or in understanding the physics of our universe, but also in advancing our scientific knowledge in multidisciplinary areas of science.

A dusty (or complex) plasma is a normal electron-ion plasma with and additional charged component of small in micron-sized particulates. This extra component, which increases the complexity of the system even further, responsible for the name “complex plasma.” Dusty (complex) plasmas are ubiquitous in different parts of our cosmic environment, (Goertz, 1989; Bliokh et al.,1995;Shukla et al.1996;Mendis et al., 1992, 1994, 1997; Verheest 2000)namely, in planetary rings, in circumsolar and the Phobias dust rings, in the interplanetary medium, in cometary comae and tails, and in interstellar molecular clouds. In fact, the dark bands of dust, which block parts of the Orion, Lagoon, Coalsack, Horsehead, and Eagle nebulae,
Figure - 1.1 The dust disk partly obscures the central star.
Figure - 1.2 Halley's comet as jets of gas and dust are emitted from the nucleus and blown back (to the right) by the solar wind.
Figure - 1.3 Dramatic nebular clouds of dust and gas lie in the star-forming region of the constellation Monoceros.
indicate that dust must have been abundant in the nebulae that coalesced to form the Sun, planets, and other stars. On the other hand, during the Voyager 1 and 2 flybys of the other planets and the ICE flyby of comet Giaobini-Zinner, it has been demonstrated that the plasma wave instrument can detect small dust particles striking the spacecraft (Gurnett et al., 1983, 1996, 1997, 2000). Complex dusty plasmas also occur in the flame of a humble candle, in the zodiacal light (Fig. 1.4), in cloud-to-ground lightening in thunderstorms containing smoke-contaminated air over the United States, in volcanic eruptions (Fig. 1.5), and in ball lightening. A recent investigation suggests that ball lightening is caused by oxidation of nanoparticle networks from normal lightening strikes on soil.

A large fraction of the matter in the universe is in the plasma state. On the other hand, a considerate amount of solid matter in the universe is found in dust particulate form, which is often embedded in plasmas as an impurity. This type of plasma naturally (or artificially) doped with dust grains may be called dusty plasma (Geortz, 1989; Angelis, 1992).

There are two important features that distinguish dusty plasmas from the usual multicomponent plasmas. First, because of finite size and hence the large mass of the dust particles, the plasma as well as the gyro frequencies of the ions and the dust are widely separated and, consequently, it is possible to separate the model arising due to the dust and ion inertial effect (Rao, 1993). Second, the charge on the dust particles can vary owing
Figure - 1.4 Zodiocal dust system (a) Sunset, (b) 1 hour after sunset, with zodiocal light extending about 50° above horizon. Zodiocal light have helped to clarify the nature of the interplanetary dust.
Figure - 1.5 Evolution of a secondary atmosphere occurs as volcanic gases and dust, are emitted from planetary interiors.
to either the wave-motion induced electron and ion currents flowing into the grain surface on the equilibrium charging process (Allen 1992, Barenes et al. 1992). The latter are known to be responsible for certain new effects in dusty plasma which are absent in multi component plasmas with different types of ion-electron species for example, it has been known recently that the grain charge fluctuations typically give rise to damping of the waves which should otherwise propagate as a normal modes (Varma et. al. 1993; Melandso et. al. 1993; Rao and Shukla, 1994).

The physical process in dusty plasma have been studied intensively because of their importance for a number of application in space plasma, (Goertz, 1989; Angelis 1992; Northrop 1992), the earth's environment and in laboratory and several technologies (Sheehan et al.,1998;Carlile et al.,1991;Jellum et al.,1991). The interesting features of a dust particle as its variable size, mass and shape and mainly its fluctuating charge. Generally dust particles are highly charged($Q_d = 10^3$ e-10^6 e) with variable sizes (10 nm-100 μm) and masses. (10^{-14}-10^{-12} g). (Shukla 2000). Though the assumption that dust particles are spherical point masses of equal size (i.e. equal radius) will not introduce much error, the charge acquired by them must be taken into account.

Lately, the physics of dust (complex) plasmas has appeared as one of the most rapidly growing fields of science, besides the field of Bose-Einstein condensates, as demonstrated by the number of published papers in
scientific journals and conference proceedings. It has a tremendous impact in astrophysics and low-temperature laboratory discharges including processing plasmas in the semiconductor industry. While in the latter one wants to clean up charged dusts which are anathema to microchips, charged dust grains are also deliberately created in low-temperature radio frequency and glow discharges to understand the basic physical processes associated with the presence of those grains. In laboratory discharges, one is able to study the growth of dust grains under gas densities and temperatures typical of the nebula from which the solar system was formed. The particulates look like tiny cauliflowers (Prabhum et al., 1995, 1996) pressed together in irregular strings a growth pattern that offers clues to the rate at which dust particles in interstellar space turned into the clumps of matter, which are large enough to assemble into planets due to gravity. Irregular structures of charged dust particulates also appear in tokamaks.

Dusty (complex) plasmas are fully or partially ionized low-temperature gases comprising neutral gas molecules, electrons, ions, and extremely massive charged sub micron and micron sized dust grains. The latter, which are a billion times heavier than the ions, acquire several thousands of electron charges. The dust grain charging occurs due to a variety of physical processes including the collection of the background plasma electrons and ions by dust grains, the photoelectron emission, secondary electron emission, and harmonic emission, etc. (Mott-Smith et al., 1971; Rosenberg et al., 1995, 1996, 1999; Barkan et al., 1994; Walch et
al., 1994, 1995; Sikafoose et al., 2000; Fortov et al., 1998; Boeuf et al., 1999; Goertz et al., 1984; Whipple et al., 1985). Dust grains can be charged both negatively and positively. The grains act as a force of electrons when they are charged positively due to the irradiation of ultraviolet (UV) radiation. Both the positive and negative dust grains can coexist in laboratory and space plasmas, it appears that the dust grain charging is a new physical process in a dusty plasma, which marks a distinction between the latter and the usual multicomponent electron-ion plasma containing two ion species.

Furthermore, meteoritic dust is thought to be present in the Earth’s mesosphere at altitudes of 80-95 km. (Fig: 1-6.) It has been conjectured that in the cold summer mesopause, ice particles can form around meteoritic dust particles, with the icy dust particles possibly influencing the charge balance of the region (Cho, 1993; Zao et al., 1997). On the other hand, the presence of charged dust particles in the polar summer mesopause has been invoked to explain aspects of the very strong polar summer radar echoes referred to as polar mesosphere summer echoes (PMSE), which occur at altitudes of 80-93 km. Recently, the presence of charged dust in the mesosphere has been detected by direct rocket probe measurements, and both negatively and positively charged dust grains have been reported (Havnes et al., 1996). The role of charged dust in mesospheric electric fields is recognized by Zadorozhny (Zadorozhny, 2000). The formation of an artificial dusty plasma in the ionosphere was also revealed during the Space
Figure - 1.6 Meteoric dust (a) The shower of November 17, 1966. (b) The intense Leonid shower of November 12, 1833. The meteors were described as "falling from the sky like snowflakes". (NASA)
Figure - 1.7 Structure and features of Earth's atmosphere.
lab 2 mission when the space shuttle orbital maneuver system engines were fired (Bernhardt et al., 1995).

Since dust particles are a main element of interest in the solar system and in the interstellar medium, there are a number of future missions (viz. the European Space Agency-ROSETTA mission for detecting dust on comet 46P/Wirtanen in 2012, the Cassini spacecraft mission arriving at Saturn in 2004 for exploring in detail the possible dust size, dust charge, dust dynamics, as well as other collective processes involving charged dust grains) that will provide in detail the properties and global dynamics of charged dust grains. It is anticipated that future rocket campaigns in northern Scandinavia will provide more information regarding the mesospheric dust, while experiments on the international Space Station will determine the dusty plasma behavior under micro gravity conditions.

1.2 Kinetic Alfvén wave with dusty plasma:

Hannes Alfvén, lifetime fellow of IEEE Swedish physicist and 1970 Nobel Laureate for physics, after a life of exceptional scientific achievement, his discoveries laid the foundations of major parts of modern plasma physics and its applications in areas as diverse as industrial processes, thermonuclear research, space physics, astrophysics and cosmology. His discovery of a new kind of waves, now called Alfvén waves, was initially met with disbelief and accepted only years later. With the evolution of plasma physics, and space plasma physics, the significance
of this discovery has related terms such as Alfven velocity, Alfven number, etc., have become among the most frequently used terms in plasma physics. Alfven waves in a plasma were first separated and detected by Allen 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.

Thus the Alfve’n wave is the dominant low frequency transverse mode of magnetized plasma, which displays a continuous spectrum even in the bounded plasma. This is mainly due to the degeneracy of the wave characteristics, i.e., the frequency (ω) is primarily determined by the wave number in the direction parallel to the ambient magnetic field (k∥) and is independent of the perpendicular wave numbers, the direction along which the wave energy propagates, is identical to the ambient magnetic field lines. Therefore, the spectral structure of Alfve’n wave has a close relationship with the geometric structure of the magnetic field lines. In an inhomogeneous plasma, the Alfve’n resonance (ω - C_A k∥ = 0, C_A is the phase velocity of the Alfve’n wave) constitutes a singularly for the defining wave equation, this results in the continuous spectrum.

The kinetic Alfve’n wave is the Alfven wave for which wave-particle interactions are important. The parallel electric fields along magnetic field lines arise mainly due to finite larmor radius correction to the usual MHD Alfve’n mode. These short wavelength Alfve’n waves are called kinetic
Alfven waves. Kinetic properties of the Alfve’n wave which originate from the finite perpendicular wavelength effects are studied well in past. The wave accompanies a parallel electric field and can propagate in the direction obliquely to the ambient magnetic field. The kinetic Alfve’n wave can be excited in a plane either by drift wave instability or resonant mode conversion of a surface magneto hydrodynamic wave.

Many theoretical attempts have been made to apply the kinetic Alfven wave instability to magnetospheric dusty plasmas; most of them lack a careful cheek as to the applicability of the theory. The KAWs have vast applications to heat Tokamak-type plasmas to the thermonuclear temperatures. KAWs are found to have a two dimensional structure with electrostatic and magnetic components with phase velocity (parallel to the external magnetic field $\mathbf{B}_0$) much smaller than the electron thermal velocity.

The kinetic Alfve’n wave was first introduced by Hasegawa and Chen (1975) in relation to plasma heating. Hasegawa and Chen (1978) introduced that kinetic Alfve’n wave propagates into the higher density side of the plasma and after the mode conversion dissipates due to both linear and non-linear processes and heats the plasma. They have discussed the application to diffusion of radiation particle and ring current heating of plasmopause electrons and formation of the stable auroral red arcs as well as viscous interaction between the solar wind and the magnetosphere.
Kinetic Alfven waves are of great importance in laboratory and space plasmas. These waves may play an important role in energy transport, in driving field aligned currents, in particle acceleration and heating in the Earth’s magnetosphere, in explaining inverted-V structures in magnetosphere-ionosphere coupling, in solar flares and the solar wind and ultra-low frequency (ULF) emission in the Earth’s magnetosphere. (Fig:1.8,1.9 &1.10)

The damping effects of the kinetic Alfven waves in dusty plasmas introduced by charged fluctuation of the negatively charged particles allow the localized energy to propagate away from the Alfven wave itself and thus deposite the surface wave energy into the plasma. The resonant absorption of Alfven waves in an inhomogeneous medium may find applications for the heating of fusion plasma in laboratory like \( \alpha \)-particle driven kinetic Alfven waves and the heating of solar corona –like sheared Alfven waves coupled with surface waves ,reminding us of the presence of dust particles in every environment of the universe Fig. 1.11. Our present study may also help us to understand the filamentary structures existing within the diffuse the aurora if the plasma is taken to be inhomogeneous. The aurora is part of the overall interaction of solar wind ,the earth’s magnetosphere, and the earth’s atmospheric particles, viz ,oxygen and nitrogen particles(Das et al.,1996). When these spectacular displays of luminous radiation (auroras) in the arctic skies are examined carefully, some clear microscopic patterns,
Figure - 1.8 A three-dimensional view of the Earth's magnetospheric cavity, the large-scale current systems in and around the magnetosphere, and the connectivity to the ionosphere.
Figure - 1.10 Solar wind
Figure - 1.11 Solar Corona
such as the discrete arcs having certain shapes with spacings of a few tens of kilometers, are observed.

In $\alpha$-particles driven by kinetic Alfven waves, linear $\alpha$-landau resonance provides the instability, whereas in dusty plasmas, dust charge fluctuations will provide the instability when the dust particles are positively charged, since negatively charged dust charge fluctuation lead to wave damping. Due to the preferential capture of electrons, dust particles are generally negatively charged and hence kinetic Alfven waves in dusty plasmas are normally damped. On the other hand, $\alpha$-particles driven by kinetic Alfven waves generally grow (unstable). Here we note that $\alpha$-particles driven by kinetic Alfven waves are the phenomenon related to laboratory plasmas (tokomak) with much more complicated situations like diamagnetic drift, particles and magnetic field (having radial and polodial components) gradient, etc., whereas the kinetic Alfven waves in dusty plasmas proposed by us may be relevant to space as well as laboratory plasmas. The occurrence of kinetic Alfven waves in dusty plasmas dominated by the dust particles collective dynamics.

1.3 Dusty Ionosphere:

The ionosphere is the ionized portion of the atmosphere extending from about 100 km. above the Earth’s surface to several 1000 km. It results from the directed interaction of the extreme ultraviolet (EUV) radiation from the Sun with the upper atmosphere, which thus serves to shield the
Earth and all of life. Although the ionosphere is created by the solar (UV) radiation, at high latitudes, localized regions of additional highly variable ionization are created when energetic electrons precipitate into the lower ionosphere from the magnetosphere above. Such events are associated with the northern and southern aurora. The ionized and neutral gases are tightly coupled via collisions, and hence their dynamics are coupled, responding to energy and momentum drivers from both the magnetosphere above and the troposphere below.

From a practical standpoint, the ionosphere enables long distance radio wave propagation to take place over a wide spectrum of frequencies. Perturbations in the ionospheric density however, lead to the disruption of HF radio communications and navigation systems (e.g. degrading the accuracy of the Global positioning system, or GPS). Such perturbations are caused by a variety of factors still not understood, including geomagnetic forcing and variable solar and tidal forcing. Geomagnetic activity also drives intense, rapidly varying electrical currents in the ionosphere at high latitudes, which can damage power grids through the induction of large potential drops. (Fig:1.12)

In winter, with at best a very oblique solar illumination, the polar ionosphere sounded by incoherent scatter radars is predicted to be rather depleted. Whoever, observations from the Eiscat Svalbard Radar (ESR) or Sondre Stromfjord reveal numbers of structures with high electron densities
Fig.-1.12 Polar plot of the ionospheric convection (white lines) and potential distribution (color code) in the northern polar ionosphere
which can cover a wide altitude range (Nilsson et al., 1996; McCrea et al., 2000). Intense signatures also appear in the temperature and velocity profiles, but their correlation with the density structures is not always obvious. In these cases the ionization production depends on other sources than the reduced solar illumination, mainly, the magnetospheric particle precipitation or, in the F region, ionization transport from lower latitudes better illuminated by the Sun.

The large number of radar, optical, and magnetic observations at auroral latitudes collected for several decades has motivated the development of theoretical and numerical works on the precipitation process. After the first works by Ress (1963) various studies concentrated on auroral precipitations. They quantified the energy degradation of the plasma sheet electrons and ions penetrating the high atmospheric layers, the altitude range and the rate of the ionization production, and the heating of the thermal plasma as a function of the incoming particle flux and energy (Rees. 1987; Kirkwood and Osepiian, 1995; Galand et al., 1999). The polar ionosphere has been explored more recently. On the dayside it is connected to the cusp region or to the boundary layers, and the precipitation fluxes from these regions present quite different characteristics from the auroral zone. In the cusp the average electron energy is typically of the order of few hundred eV, as compared to a few keV in the auroral zone. Consequently, the energy deposition occurs in the F region and not in the E region as for keV electrons. The protons remain energetic in the cusp, up to
a few keV, and their fluxes can even reach larger intensities than in the auroral zone. Galand et al., [1999, 2001] showed that intense fluxes of energetic protons produce significant ionization in the E region. In the cusp they are expected to be responsible for the whole production below 160-km altitude. From simulations of the cusp precipitation effects on various ionospheric species (Millward et al., 1999) similarly concluded that both ion and electron precipitation are important sources of ionization but at markedly different altitudes depending on their energy. One reason is the energy difference between the precipitating electrons and protons, but it is not the only one. Electrons and protons deposit their energy in a different way. The ionization peak is more sensitive to altitude for electrons than for ions (Galand et al., 2001). Effects of cusp precipitation should concern other plasma parameters, in particular, the electron temperature, but they have been much less investigated that the ionization production.

In the daytime the polar radars are expected to observe the ionospheric footprints of the cusp and also of the surrounding regions such as the low-latitude boundary layer (LLBL) or the dayside extension of the plasma sheet or its boundary (BPS), depending on solar wind conditions and local time. These regions have been well identified by polar satellites. (Fig: 1.13) In particular, the observations by the satellites Defense Meteorological Satellite Program (DMSP) and Polar have provided statistical estimates of the precipitation energy and flux as a function of the geographical location, of the local time of the season, and of the
Figure - 1.13 Polar Satellite
geomagnetic activity [Hardy et al., 1985, 1989; Newell and Meng, 1992; Liou et al., 2001]. Up to now, there is no clear estimate either of their characteristic signatures nor of their differences into the ionosphere.

1.4 Dusty Magnetosphere:

The magnetosphere is an important and sizable part of the near-Earth space environment. It is not only of considerable inherent scientific interest, but a number of communications, navigation and military satellites that have become indispensable of routine human activities are stationed in this region. To ensure their accuracy and reliability, it is important to understand fully the medium in which they operate. For these reasons, there has been an ongoing attempt to understand the magnetosphere environment, its sensitivity to external forcings, and its dependence on observable parameters.

Unlike the polar region, where the magnetic field lines are open and merge with the interplanetary magnetic fields, the magnetosphere environment is characterized by magnetic field lines that are closed and approximately dipolar. This background geomagnetic field configuration leads to unique plasma dynamics that provides the magnetosphere with its distinctive characteristics. While the polar region has been extensively studied (Schunk, 1989; Ganguli, 1996), the magnetosphere has attracted comparatively less attention over the last four decades. Consequently
accurate models of the magnetosphere are still under development are being refined.

The need for a reliable model for the high-altitude magnetosphere has become especially important now because of three imaging missions, NASA/IMAGE (Burch, 1996), DoD/ARGOS (McCoy et al., 1995), and the proposed magnetospheric Imager (MI), whose objectives include imaging the magnetosphere. As explained by Roelof et al. (1992), an important but substantially unresolved issue confronting remote sensing experiments is the extraction of qualitative and quantitative physical information from the observational data. Satellite imagers will record the UV sunlight scattered from He⁺, O⁺ and other ions in the magnetosphere.

The various layers of geospace respond to solar variability in different ways depending upon their nature and the changes they experience. The magnetosphere is the local region of interplanetary space from which the solar wind is largely excluded by the Earth’s magnetic field. It is filled with a very hot, tenuous ionized gas (i.e., a plasma), which is so optically thin that it does not interact with solar radiation in any significant way and is effectively invisible. The magnetosphere is the first line of defense against the energetic charged particles and solar wind plasma directed toward the Earth. However, intense intervals of solar activity, like those producing coronal mass ejections can result in dramatic increases in the inner magnetosphere’s radiation belts and geomagnetic activity. (Fig: 1.14a[17]
Fig.-1.14a 3D representation of the near solar region (Before the initiation of the CME). The color represents log ($B$) in the ($x$, $z$) and ($x$, $y$) planes. Solid lines are magnetic field lines; magenta denotes the last closed field lines, red is open field lines expanding to the interplanetary medium just above the heliospheric current sheet, and finally, white lines show open magnetic field lines in the ($y$, $z$) plane.

Fig.-1.14b 3D representation magnetic field lines (9 hours after the initiation of a CME). Color code represents log ($B$), white lines are open magnetic field lines, magenta lines represent magnetic field lines with both ends connected to the Sun.
&1.14b) These geomagnetic storms and sub-storms result in large amounts of energy being transmitted to the upper layers of the atmosphere through energetic particle precipitation and electric currents. (Fig:1.15)

In a real sense, however, the thermal plasma of the ionosphere traps the magnetic field at magnetospheric heights. We are aware of the fact that a magnetic field can penetrate a good conductor only slowly, thereby changing the field in it. What happens if that the changing field induced current in the good conductor, which tend to cancel the field where it would penetrate and to strengthen it outside that region.

It is reasonable to enquire under what conditions plasma controls the field and when the field moves the plasma. It is a matter of energy density, when the thermal energy density in the plasma exceeds the magnetic energy density in the field, plasma controls the field, and if there are already field lines in the plasma they will tend to be carried with it in any motion, which the plasma has, such a field is said to be frozen in. If the energy density in the magnetic field exceeds the thermal energy density in the plasma, then the plasma will tend to be moved by any motion of the field lines.

The line of the geomagnetic field are frozen into the ionospheric-magnetospheric plasma, and motion of the plasma distorts the field. On the other hand, the trapped radiation is so much less dense that, in spite of the great energy of the particles, they do not significantly disturb the field as a
Fig. 1.15 3D representation of magnetosphere around the Earth
whole, as is evidenced by the fact that geomagnetic storm variations at the Earth are a small perturbation on the mean value.

1.5 Magnetosphere Ionosphere Coupling:

It is a transient phenomena when the high energetic solar wind particle with high velocity enter into the magnetotail by reconnection process and travel along to the magnetic field and hit to the ionosphere region the aurorae (luminous glow of charged particles) occur. This process is called magnetosphere-ionosphere coupling or events.

In a magnetic field, charged particles gyrate around the magnetic lines of force with velocity $V_\perp$, and stream along those same lines of force with velocity $V_\parallel$. In a dipolar field configuration (Fig. 1.16 ), there is an exchange between parallel and perpendicular energies so as to maintain the constancy of the dipole moment $N = \frac{1}{2} \frac{m v_\perp^2}{B}$ (where $m$ is the mass of the charged particle). This leads to the particles bouncing between mirror points located above the ionosphere in the northern and southern hemispheres. In addition, the gradient in the Earth’s magnetic field as one move away from the Earth leads to azimuthal drift of the particles around the Earth. In addition to this the component of the electric field $E$ perpendicular to the ambient magnetic field $B$ results in convective drift in a direction normal to both $E$ and $B$ with velocity $E \times B / B^2$ whose magnitude is $E / B$. Thus the electric field, by moving the energetic particles around in the magnetosphere, effectively influences the transport of energy from one part
Figure 1.16
of the magnetosphere to the other. In addition, this electric field maps to the ionosphere where it can derive electric currents in the conducting channel marked by the auroras (where energetic particles not only excite the atmospheric constitutions to produce auroral luminosity but also ionize that portion of the atmosphere between 100-200 km. creating a good electrical conductor). Let us now look at the results of the interplay between E and B as regards the electrical systems.

Locus of auroral activity (the auroral oval) at high latitudes, (Fig. 1.17), which is present at all times with variable intensity. On the dayside predominantly red auroras are generated by low energy (hundreds of eV) electrons bombarding the ionosphere directly formed the magnetosheath (it is thought). On the nightside the auroras are dominantly green, generated by higher energy (several keV) electrons, which originate in the plasma sheet. While the dayside auroras are relatively quiescent, the nightside auroras may suddenly intensify explosively marking the signature of a major magnetospheric energy dissipation episode termed a substorm. The electric field configuration, is shown by (Fig. 1.18), observed in the ionosphere. In the auroral regions, the E fields are primarily north south, while in the polar cap E is directed from dawn to dusk. Two types of currents are driven by the electric field. There is, of occurrence, the direct or Pedersen current flowing parallel to E. However, in a thin region of the ionosphere between 100-200 km, the $E \times B/B^2$ drift of ions and electrons is influenced by the fact that the ions tend to collide more often with the neutral background gas
The Auroral Oval

Figure 1.17
The auroral oval featuring auroras rich in red on the dayside and rich in green on the nightside
The Auroral Electrojets

E – The convection electric field
I – Hall current which flows because
\[ \mathbf{V} = \mathbf{E} \times \mathbf{B}/B^2 \] and near 100 km
ions are impeded by neutrals more than electrons

Figure. 1.18
The electric field configuration in the auroral oval
and the Hall current electrojet directions
than do the electrons (because of the difference in the collision cross sections). For a northward electric field (in the evening sector) the electrons and ions both drift westward, however, the fact that the ions are more impeded than the electrons leads to an eastward current termed the Hall-current. In the morning sector the southward E field results in a westward Hall-current. The east west currents flowing in the auroral oval are called the auroral electrojets. It is interesting to point out that, for Pedersen currents \( J_p \cdot E > 0 \) indicating that energy is dissipated. Thus, somewhere there must be an electrical generator providing energy for the circuit involving the Pedersen currents. On the other hand, for Hall current \( J_h \cdot E = 0 \) and thus no energy is dissipated and no generator is required. It should now be noted that current can not start "in the middle of nowhere".

Satellite and ground based magnetometer studies have revealed that there is downward current flow across the noon sector auroral oval, which diverges into the ionosphere to feed the eastward and westward Hall electrojets. These electrojets come together in the evening sector where the ionosphere current diverges to flow out of the ionosphere parallel to the magnetic lines of force. The three dimensional current system involving the Hall electrojets is shown in (Fig.1.19).

Now the auroral oval acts as a high conductivity channel, so that current continuity conditions demand the north-south Pedersen currents diverge into and out of the ionosphere at the conductivity discontinuity.
Current Input and Output

Figure 1.19

The field-aligned currents feeding the Hall current electrojets
between the dark ionosphere and the part of the ionosphere activated by particle bombardment. The parallel current sheets are called Birkeland currents, and their configuration has been well established by satellite magnetometer measurements. The entire complex E field and current configurations are shown in (Fig. 1.20).

Now let us address the question of how these current systems close in the magnetosphere and where (if necessary) the generator regions are located. First let us consider the three dimensional circuits involving Pedersen closure currents in the ionosphere and therefore must involve a generator region in the magnetosphere. For the evening sector the ionosphere closure current flows poleward and connects to field-aligned current flowing downward in the equatorward portion. One of the present views is that closure in the distant magnetosphere is affected by currents flowing normal to the magnetic lines of force. Since the electric field, which is poleward in the ionosphere, maps into the magnetosphere in such a way that magnetic field lines may be considered as electric equipotentials. It can be seen that in the magnetotail the closure currents are antiparallel to E precisely the condition for an electric generator. In fact, the closure currents flow because a magnetohydrodynamic generator mechanism is operative which extracts energy to drive the current system from the E x B drift motion of the plasma sheet. Now, while energy must be extracted from the drifting plasma to derive electric circuits, which have Pedersen closure currents in the ionosphere, such is not the case for current systems, which

[22]
Energy Budget in the Auroral Oval

Figure 1.20

The complete high latitude current configuration in the auroral oval

\[ V = Ed \]
\[ P = VI = I^2R \]

For the Auroral Oval

\[ E \sim 50 \text{ mV/m} \]
\[ d \sim 500 \text{ km} \]
\[ I \sim 5 \times 10^5 \text{ A} \]
\[ P \sim 10 \text{ GW} \]
\[ R \sim 1/25 \Omega \]
have Hall closure currents in the ionosphere. In the later cast, a simple change in the direction of plasma convective flow is all that is needed. This can be understood from the fact that a change in flow direction is equivalent to having vorticity in the plasma flow. If $E + V \times B = 0$ is valid, then one may use Maxwell's equation $\nabla \times E = \frac{\rho}{\varepsilon}$ to show that where there is plasma vorticity, there must be space charge $\rho = (-B \cdot \nabla \times V)$. Fig. 1.21, shows plasma flow lines in the magnetosphere, and it can be seen that the flow configuration is consistent with positive space charge near the magnetopause in the per-noon quadrant and negative space charge tail ward of the dusk Meriden. Not only is the charge configuration consistent with the well-known dawn to dusk electric field across the magnetosphere, but in addition one would expect electric currents to flow in an effort to neutralize the space charge distributions.

This leads one to ask how the field-aligned currents involved in this "discharge" process are driven—that is, what are the current carrying a particles. In the per-noon quadrant there is not problem in that cold electrons can be drawn out of the ionosphere to neutralize the positive space charge distribution near the dayside magnetopause. The upward flowing electrons constitute a downward current and the large number of ionospheric electrons available coupled with their relatively high mobility along the field lines in the topside ionosphere combine to give the magnetosphere no trouble in generating the downward current which feeds
$E = V \times B \rightarrow \nabla \cdot E = \frac{\rho}{\varepsilon_0} = -\nabla \cdot (V \times B)$

$\rho \approx -\varepsilon B \cdot \nabla \times v$

**Convection and Space Charge in the Magnetosphere**

**Figure 1.21**

Plasma flow lines projected on the magnetospheric equatorial plane. Vorticity in the flow is consistent with a space charge distribution whose discharge would produce. The observed three-dimentional current system involving the Hall current electrojets.
the auroral (hall current) electrojets. The problem of driving upward field-aligned currents in the premidnight sector is quite another matter. Upward current can either be carried by upward moving protons or positive ions, or by downward moving electrons. Unfortunately the upward mobility of ionospheric protons and positive ions is rather limited and the numbers of magnetospheric electrons, which can be driven into the ionosphere, are quite small. Thus the magnetosphere is faced with a problem in trying to match the upward and downward field-aligned current flow in the Hall current circuits. The recent discovery of an acceleration region in the altitude range 2000-10,000 km. above the auroral oval has allowed us to make major steps forward in our understanding of how this matching of field-aligned currents can take place. Daring the interval 1975-77 indirect measurements of high altitude electric fields by using E x B drifting barium clouds and direct measurements in situ using electric field probes combined to yield the following facts. Somewhere between 2000 and 10,000 km. altitude was a potential drop, which was capable of accelerating electrons to energies of several keV and driving them into the high latitude ionosphere where they could stimulate auroral emissions. At the same time, ions were accelerated upward along the magnetic lines of force into the outer magnetosphere. This situation is shown schematically in (Fig. 1.22). Not only do the accelerated electrons stimulate auroras but by the very fact that they are lost in the ionosphere they constitute a net upward field-aligned current. Above the acceleration region the protons and heavier ions (e.g. O⁺) carry the
Figure 1.22

The acceleration region above an auroral surge. Energetic electrons are accelerated into the ionosphere where they cause discrete auroras, and positive ions are accelerated upwards. Both sets of accelerated particles carry upward current.
upward current. Thus the magnetosphere maximized the upward current by using an acceleration mechanism to maximize the velocity of the current density $J = n e V$, the upward current is maximized by maximizing $V$ while the downward current takes advantage of the large number density $n$ of available ionospheric electrons. If the downward flow at the front side of the magnetosphere is increased through an increase in the level of the solar-terrestrial interactions, the night side upward current can only be enhanced through operation of the accelerator. This leads to the production of keV electrons and their precipitation leads to marked enhancements of auroral luminosity. In fact these episodes of acceleration in a given region of space develop rapidly (in a matter of seconds) and die down after a few minutes. The process for accelerating auroral electrons appears, therefore, to be characteristic of an instability. A magnetospheric substorm can be thought of an instability. A magnetospheric substorm can be thought of as a sustained series of such acceleration episodes.


[25]

The most visible manifestation of the solar terrestrial interaction regarding the magnetosphere and ionospherical dynamics is the aurora borealis observed at high latitudes in the northern hemisphere and their counterpart, the aurora borealis, observed in the southern hemisphere. These dynamic displays of the multicolored luminosity have fascinated 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 out on a firm basis. In the early 1920’s certain facts were clear. The aurora was associated with an electrical discharge phenomenon, and the luminosity was due to the excitation of atmosphere. In fact the great Norwegian physicist, Kristian Birkeland, 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 the ionosphere. Thus the scientists were able to infer the physical processes which directly led to the aurora.

The auroral excitation was caused by the very same particles, which carry the current whose magnetic effects are observed on the ground as a polar magnetic sub-storm. Although our modern view of the auroral polar magnetic sub-storm relationship has a greater level of complexity than Birekeiland’s original concept, the idea that the current is carried by the

[26]
particles precipitating from the outer parts of the earth's environment remains intact. We now know that auroral ionospheric currents are indeed connected via currents along field lines with the magnetosphere. However, the occurrence of aurora does not necessarily require the existence of net flow of current in the region of the aurora. Stated differently, precipitating electrons cause auroral excitation, but the current that they carry may be cancelled by the effect of precipitating protons and/or upward streaming low energy ionospheric electrons.

Numerous rocket and satellite measurements of the particles associated with aurora have been made and some in Situ observations of the magnetic field above the polar ionosphere have been obtained as well. In addition several studies have been carried out correlating satellite and ground based magnetic data, thereby enhancing the interpretation of the data in terms of magnetosphere-ionosphere coupling via field-aligned current.

1.6 Summary:

Effects of dust particles on magnetosphere-ionosphere coupling are discussed. In this reference we have attempted to review the main results and new aspects of the last decade in the field of auroral research as electric field and currents in the high latitude ionosphere and field-aligned currents and their relationship to the large scale distribution of auroras in magnetized dusty plasmas. Field-aligned currents, auroral accelerations, dusty ionosphere dusty magnetosphere, parallel electric field are discussed. A
time dependent unified theory considered the kinetic Alfvén wave with dusty plasma to explain most of the phenomenon related to magnetosphere- ionosphere coupling system. The brief discussion given in this chapter are also included solar wind, dusty corona, meteorites, comets, star formation process, dust clusters, etc. The utility of this work is incorporated in the upper atmospheric region.