CHAPTER I

INTRODUCTION

1.1 Objectives:

The physics of plasma is an extremely important discipline for understanding the different processes of the universe, because 99.9% of the apparent universe exists in the plasma state. However, there is very little in the state of natural plasma on the earth, as the low temperature and high density of the earth and its near atmosphere preclude the existence of plasma. This only means that the plasma must be created in the laboratory by experimental means so as to study its property and different physical processes occurring in it. However, the study of space plasma phenomena is difficult in a laboratory where the simulation of such plasmas is not always possible because of small dimensions of plasma system in the laboratory.

The direct experimentation wherever possible, with naturally occurring space plasmas and the investigation of the associated phenomena appear to be a more justifiable approach to the study of plasma physics, in particular and to the understanding of nature, in general. The earth's upper atmosphere known as ionosphere, is one of such natural plasma laboratories which is easily accessible to a plasma physicist.
1.11 Importance of Ionospheric Plasma Research:

Throughout the history, every advance of mankind in the extension of his world has brought with it problems of communication. Today, more than ever, man's exploration of unknown territories depends upon communication. Each advance of man into space must be preceded by remotely operated unmanned probes and by the transmission of vast quantities of information concerning the space environments. With the development of rockets, satellites, and other space probes, our knowledge of the space environments in the immediate vicinity of the sun and its planets has progressed by leaps and bounds. Our knowledge of plasma physics, in general, and atmospheric phenomena, in particular, have played a major and important role in radio communication studies.

The earth's upper atmosphere is the region wherein the ionizing radiations from the sun have caused sufficient ionization for the reason to be termed as partially ionized plasma. This naturally occurring partially ionized plasma which is embedded in earth's magnetic field, is termed as 'ionosphere' which can be defined as a conglomeration or mixture of neutral, positive and negative charged particles in a state of dynamic equilibrium such that the loss of charged particles by recombination is balanced by the creation of new ones via some energy input mechanism. It goes through periods of relative calm as well as through stormy and turbulent phases, but never actually settles down to perfectly calm or static state.

The ionosphere has entered into the everyday life of
most persons because of its role played in long distance communication and broadcasting. The ionosphere modifies the propagation characteristics of radio waves in transit. Waves of certain frequencies can be bent sufficiently by the ionosphere to make long distance communication possible between different earth and space stations. Although microwave communication via satellites is becoming increasingly popular in recent years, short wave communication is restricted to the ionosphere and is largely controlled by the ionospheric plasma conditions. Anyone who has ever listened to a short wave radio broadcast has experienced the effects of the dynamic ionosphere in the form of apparently random fading of radio signals; time variation in received signals strength must reflect time variation in the propagation medium. Clearly, then an understanding of the ionospheric plasma as a telecommunication medium would be incomplete without the study of its dynamic behaviour and its associated phenomena. Besides communications, the ionosphere is also relied upon as an indicator of surveillance activities.

A weakly ionized plasma immersed in magnetic and electric fields is susceptible to various kinds of instabilities which manifest themselves as wavelike perturbations of electron density and electric field. The ionospheric plasma under different conditions, therefore, exhibits these natural perturbations termed as 'irregularities'. HF radio waves undergo rather easily measurable perturbations and distortions while travelling the ionosphere. These irregularities and
their dynamic characteristics can affect every characteristic by which a radio wave is specified; its amplitude, phase, frequency, polarization, direction of arrival, etc. Fluctuations (which are almost wavelike or nearly random in character) in these quantities occur because of these wavelike or some other types of ionospheric motions or irregularities.

It is quite well understood how the various radio propagation effects, such as scattering and fading of HF radio signals, refraction and oscillations in the intensity of solar and galactic radio emissions, radio star and satellite scintillations, can arise if irregularities in ionization densities which are mostly aligned with earth's magnetic field, are present in the ionosphere. In view of the important role played by the ionosphere throughout a wide range of wavelengths (from short waves right up to the wavelength of tens of kms or more), it is impossible to understand the propagation of radio waves without a thorough study of the irregularities generated in the ionospheric plasma. Consequently, the investigation of the ionospheric irregularities and their associated generation mechanisms, which influence greatly the radio wave propagation, is interesting and vitally necessary for a proper functioning of radio communication and other networks.

In the last decade or so, there has been a great upsurge in interest and activity on both the experimental and theoretical sides. There are still many fundamental gaps and contradictions about the explanation of the irregularities, their generation mechanisms and their characteristics. Many
experimental means have been employed having accumulated a huge quantity of data some of which are confusing and conflicting. Theories are yet to be developed to explain satisfactorily the existence and the production of these irregularities and their associated phenomena. The difficulty lies in the fact that so many factors and parameters exist in the study of ionosphere that it becomes almost impossible to take them all into account simultaneously. Observations show that these irregularities are generated at various heights at different times of the day in different geographic regions and over a wide range of wavelengths under a wide variety of circumstances. Because of the complex nature of the phenomena, it seems reasonable to believe that there are many different physical processes that are responsible for the cause of ionospheric irregularities. Some of the irregularities are certainly caused by plasma instabilities, but in most cases the instabilities operate only at the wavelengths longer than the gyroradius of the particles.

Some features of the different phenomena associated with these irregularities have become clearer, a few of them have been explained and others have apparently become more complicated by new observations. Various theoretical approaches have been tried, but a satisfactory instability theory is yet to be developed. The more fundamental task, however, is to explain the generation of the irregularities themselves in different regions of the ionosphere. The investigation of the generation mechanisms and the explanation of the
different features associated with irregularities would not only be helpful to us in developing a deeper understanding of nature, but would also provide us with an insight towards an excellent HF radio wave communication and satellite navigation with very little possibility of interception by unwanted parties (irregularities) in the ionosphere.

1.12 Main Purpose of the Investigation:

The principal goal of the work presented here is concerned with the theoretical investigation of different plasma instability mechanisms which are responsible for the generation of ionization density irregularities observed in different regions of ionosphere and which could explain some of their observed characteristics satisfactorily. An attempt has been made to study these processes in both the linear and nonlinear regimes. Emphasis has been given to the relevance of these mechanisms to the equatorial ionospheric regions only.

Linear plasma instability theory appears to account only for the presence or absence of irregularities. The ionospheric plasma may develop a nonlinear state due to preponderance of various instabilities under different conditions. Thus, a nonlinear theory of the instabilities is essential to understand their development in details. A nonlinear instability theory is capable not only of explaining the nonlinear phenomena such as instability saturation, irregularities amplitude, the wavelength distribution, the propagation velocity, etc., but also of attaching considerable interest to a clearer understanding of the basic behaviour
of plasma instabilities and in turn, to the physical investigation of the real states of plasma in which it is most likely to be encountered in nature. In the present study, a modest attempt has been made to develop, separately for the equatorial E- and F-regions, the nonlinear instability theories which seem to be capable of explaining most of the features of irregularities observed and their associated phenomena such as equatorial sporadic-E and spread-F. These investigations may, therefore, be quite helpful in deducing much about the structure of the equatorial ionosphere, an important medium for HF radio wave communication.

1.2 A Short Description of Ionospheric Plasma, Its Structure and Dynamics of its Constituents:

1.21 Ionosphere as a Plasma Medium and its Structure:

From what has been said above, one feels that the knowledge of basic ionospheric plasma is fundamental to any radio communication studies. Communication involves the propagation of radio waves (electromagnetic waves) in a plasma medium (ionosphere) at different frequencies and the interaction of these waves with the medium. In the physics of a plasma, waves occupy an important position and the concept of a wave in the medium is quite familiar. The waves are generated in the plasma medium because of instabilities excited and may be considered as perturbations on the slowly changing background. These waves in the medium, which are known as 'irregularities', have two basic properties associated with them: firstly, energy is being propagated from one point to another; secondly, the
disturbances (irregularities) travel through the medium without giving it, as a whole, any permanent displacement.

Ionospheric plasma is susceptible to a number of instabilities. Because of their excitation under different conditions prevailing in the medium, it is capable of sustaining a large number of irregularities (wave-like perturbations). This thesis deals with the type of irregularities that are most important in a particular compressible medium, such as ionosphere, that is permeated by density gradients, temperature gradients and electric fields.

As the plasma medium responds to disturbances (irregularities) originating in it, their characteristics give considerable insight into the properties of ionospheric plasma. Conversely, the ionospheric plasma must be thoroughly understood to predict the character of its waves which interact with the propagating radio waves and modify the ionosphere affecting the communication.

Ionosphere is that part of the earth's upper atmosphere where ions and electrons equal in number are present in quantities sufficient to affect the propagation of radio waves. It is usually extends from about 50 km upto great heights, far our in space. Ionosphere is divided into regions called D, E and F, defined such that the part below 80 km is called D-region, that between 80 km and 140 km, the E-region and that above 140 km the F-region. These regions may be distinct layers of electrons, named D, E and F layers according to the level at which their peak occurs. However, these are not strictly demarcated layers but as described, rather regions which overlap. Sometimes these layers are marked only by a 'ledge' where the gradient is small.
There may occur more than one layer or ledge inside the single region, for example, $F_1$ ledge (with maximum around 150 km) below $F_2$ layer (with maxima around 400 km).

The charged particles in the ionosphere are embedded in a neutral gas. At some levels the neutral gas is moved by the gravitational forces of sun and moon (tidal motion of the earth's atmosphere), and probably also by the forces of thermal origins. The charged particles share this motion to some extent and since they behave like a conductor moving through earth's magnetic field, a current is induced, as in dynamo. The region of the ionosphere where this current is induced is given the name 'Atmospheric Dynamo'. Its flow is accompanied by an electrostatic field, the dynamo field (Baker and Martyn, 1953; Fejer, 1953), which reaching the other parts of the ionosphere, causes currents to flow there also. The earth's magnetic field, acting on these currents, then causes the electron-ion plasma at these distant places to move bodily. This part of the ionosphere is given the name 'Atmospheric Motor'. To a first approximation, the 'dynamo' is believed to be situated in the E-region and the 'motor' in the F-region.

1.22 Motion of the Charged Particles in Ionospheric Regions of Interest:

In the E- and F-regions, the motions of charged particles are more or less controlled by the earth's magnetic field $B$. The plasma in these regions is subject mainly to electromagnetic, collisional, gravity and density gradient forces. To study the effects of these forces, one has to
construct separate equations for the ions and electrons as they apply to ionospheric environment; that is, a partially ionized, collision dominated plasma moving in a neutral atmosphere under the forces of gravity, electric and magnetic fields. With some reasonable assumptions, the plasma drift velocity can then be found out. Negative ions are scarce in parts of the ionosphere where transport processes have any importance (except perhaps in the nighttime E-region). To a good approximation, the concentrations of positive ions and electrons can then be equated, since neutrality must be very nearly preserved. Even when electric polarization charges are developed, the difference between negative and positive charged particle densities is only one part in $10^{10}$. The rate of change of these charges is also insignificant so that if an electric current flows, it must be nondivergent. This leads to the following condition for ionospheric current densities $j$:

$$\nabla \cdot j = e \left( \nabla \cdot \left[ N_0 \left( \bar{v}_i^2 - \bar{v}_e^0 \right) \right] \right) = 0 \quad \text{...(1.1)}$$

where $e$ is electric charge, $N_0$ the number density of the charges and $\bar{v}_e^0$ the mean drift velocity with subscripts $i$ and $e$ respectively for ions and electrons. This condition is obtained by using the continuity equations for electrons and ions.

Collisions between particles are so frequent that ions and electrons can both be treated as fluids. This implies that the random thermal velocities (about $1 \text{ km s}^{-1}$ for ions and $200 \text{ km s}^{-1}$ for the electrons) cancel out so completely that
their existence can be ignored. Normally, this assumption is very well justified for thermal particles in the ionosphere. Collisions between charged particles themselves (i.e.) are negligible, because collisions of charged particles with neutral particles predominate over collisions between charged particles in a weakly ionized plasma.

a) **Transport Processes:**

The important transport processes taking place in the ionosphere are enumerated as follows:

1) The electrons and ions are greatly subject to electric fields. The resulting motions and the electric currents depend upon the magnetic field and the collision frequencies, which determine the mobility and the electrical conductivity of the charged particles.

2) The charged particles can have motions by neutral winds. These produce forces proportional to differences between the wind velocity $U$ and the charged particles velocities $v_i, v_e$ and to the relevant collision frequencies. In the E-region, the winds are normally associated with the tidal motions. Since these winds also produce the dynamo action, the physical situation is quite complicated.

3) The daily temperature changes in the thermosphere affect the charged particles as well as the neutral air.

4) Plasma tends to diffuse under the action of gravity and of gradients in its own partial pressure. The electrical forces between ions and electrons tend to keep then
together, so that both kinds of particles diffuse at same speed. This ambipolar diffusion is impeded by collisions of charged particles with neutral particles and tends to be constrained by earth's magnetic field. Diffusion proceeds more rapidly in the F-region where motions due to d.c. electric fields are insignificant to that due to diffusion, but more slowly in the lower ionosphere where collisions are more frequent and the effects due to d.c. electric and magnetic fields are significantly large.

In the ionosphere there are large scale motions in which changes take place very slowly. In this quasiequilibrium, the inertial term (representing acceleration) in the equations of motion for the charged particles may be neglected (they might not be negligible for small-scale wavelike motions). Under these conditions which exist in the ionosphere, one can write the equations of motion for the charged particles as

$$m_j \frac{d \mathbf{v}_j}{dt} = q_j (\mathbf{E} + \mathbf{v}_j \times \mathbf{B}) + m_j \mathbf{g} - m_j \mathbf{v}_j \mathbf{v}_j - N^{-1} \nabla \cdot \mathbf{p}_j^{*} \quad \cdots (1.2)$$

where $\mathbf{v}_j$ is the local mean velocity of the charged particles; $\mathbf{v}_j$, the effective collision frequency and is often termed as 'collision frequency', $p_j$ the partial pressure given by $p_j = N k T_j$ and other symbols have their conventional meanings. The subscript $j$ denotes i for ions and e for electrons. It is sometimes convenient to introduce the relative velocity $\mathbf{v}_j = \mathbf{c}_j - \mathbf{u}$ of the charged particles with respect to the neutral gss. Then equation (1.2) assumes the form as

$$q_j (\mathbf{E} + \frac{\mathbf{v}_j \times \mathbf{B}}{c}) + q_j (\frac{\mathbf{v}_j \times \mathbf{B}}{c}) + m_j \mathbf{g} - m_j \mathbf{v}_j \mathbf{v}_j - N^{-1} \nabla \cdot \mathbf{p}_j^{*} = 0 \quad \cdots (1.3)$$
The first term $q_j (\mathbf{E} + \frac{1}{c} \mathbf{U} \times \mathbf{B})$ is the force exerted on a charged particle by the total applied electric field $\mathbf{E}_0 = (\mathbf{E} + \frac{1}{c} \mathbf{U} \times \mathbf{B})$ that would be seen by an observer moving with the neutral gas. The field $\mathbf{E}$ is the electrostatic field (due to polarization charges) and the field $\mathbf{U} \times \mathbf{B}$ is often called 'dynamo field' since it corresponds to the field seen by the armature of a dynamo moving at velocity $\mathbf{U}$ in a magnetic field of a induction $\mathbf{B}$. The term $m_j g$ is the gravity force acting on the particles and the term $(N^{-1} \nabla p_j)$ represents the partial pressure gradient force which may be quite important in 'ambipolar diffusion' process (in the upper F-region where electromagnetic forces are significantly smaller). The gravity and the pressure gradient forces are usually very much smaller than the electromagnetic forces and are thus neglected to a first approximation (except when considering the motions in the upper F-region where the reverse is true). Thus the equation of motion (1.3) for a charged particle becomes,

$$m_j v_j - q_j \left( \frac{v_j \times B}{\epsilon} \right) = q_j E_0 \quad \text{(1.4)}$$

where $v_j$ is the mean relative drift velocity of a charged particle.

b) The Mean Drift Velocities of the Particles:

Knowing applied electric field $E_0$, one can determine $v_j$ from the equation (1.4). The mean relative drift velocity, $v_j$, can then be obtained as
\[ v_j = \frac{q_j}{m_j} \frac{\nu_j}{\nu_j^2 + \Omega_j^2} E_\alpha + \frac{q_j}{m_j} \frac{\nu_j}{\nu_j^2 + \Omega_j^2} \frac{E_\alpha \times B}{B} \]

\[ = \frac{c}{B} \frac{\nu_j}{\nu_j^2 + \Omega_j} E_\alpha + \frac{c}{B} \frac{\nu_j}{\nu_j^2 + \Omega_j^2} \frac{E_\alpha \times B}{B} \] (1.5)

where \( \Omega_j = q_j B / m_j c \) is the gyrofrequency of the particles, including the sign (i.e., \( \Omega_e \) is negative as \( q_e = -e \)).

It is often convenient to employ a cartesian coordinate system \((\xi, \eta, \zeta)\), whose positive \( \xi \) axis is directed along \( B \) and whose \( \eta \) axis is perpendicular to \( B \). Then, three components of the mean relative drift velocity are given by

\[ v_j \xi = \frac{q_j}{m_j} \frac{\nu_j}{\nu_j^2 + \Omega_j^2} E_\alpha \xi = \frac{c}{B} \frac{\nu_j}{\nu_j^2 + \Omega_j^2} E_\alpha \xi \] (1.6)

\[ v_j \eta = -\frac{q_j}{m_j} \frac{\Omega_j}{\nu_j^2 + \Omega_j^2} E_\alpha \eta = -\frac{c}{B} \frac{\nu_j}{\nu_j^2 + \Omega_j^2} E_\alpha \eta \] (1.7)

\[ v_j \zeta = \frac{q_j}{m_j} \frac{\nu_j}{\nu_j^2 + \Omega_j^2} E_\alpha \zeta = \frac{c}{B} \frac{\Omega_j}{\nu_j^2 + \Omega_j^2} E_\alpha \zeta \] (1.8)

The comparison of collision and gyro-frequencies of the charged particles divide the ionosphere into three regions I, II and III as shown in Fig.1.0. These regions are separated by the height \( h_0 \approx 75 \) km for which \( \nu_0 = |\Omega_e| \) and the height \( h_1 \approx 140 \) km for which \( \nu_1 = \Omega_1 \). The heights, \( h_0 \) and \( h_1 \) represent transitions for the motion of the electrons and ions respectively. Below and above these critical heights, the relations between \( \nu_j \) and \( \Omega_j \) have been shown in the Fig.1.0. Below the critical height \( h_0 \), the ions move relative to the neutral gas at the velocity \( E_\alpha q_1 / m_1 \nu_1 \) in the direction of electric field, whereas the electrons move at much greater
Fig. 1.0. Schematic representation of ionospheric regions. Also shown is the variation of electron and ion collision frequencies ($\nu_e$ and $\nu_i$) with altitude.
velocity $E_0 q_e / m_e \nu_e$ in the opposite direction. In this approximation ($\nu_j \gg \nu_e$), the magnetic field has no influence on the mobility of the particles beyond that already included in $E_0$. For constant $E_0$, the ion and electron drift velocities will increase with increasing height since the density of the neutral particles decreases and hence $\nu_j$ decreases.

Above the critical height $h_1$, the electrons and ions move with a common drift speed $c E_0 \nu_e / B$ or a common drift velocity $c E_0 \times B / B^2$, in a direction perpendicular to both the electric and magnetic fields. In addition, the particles move parallel to the magnetic field at velocities which are independent of that field and which, for a given parallel component of the electric field, continue to increase with height as $\nu_j$ decreases. In the intermediate regions between $h_e$ and $h_1$, only the electrons move with the drift velocity $c E_0 \times B / B^2$, whereas the ions remain almost stationary in comparison with the electrons. Consequently, the resulting current which flows in a direction perpendicular to both the electric and the magnetic fields, is called 'Hall current'.

c) **Currents and Conductivities:**

The presence of electrons and ions in the ionosphere makes this region electrically conducting. The concentrations of the charged particles and of the neutral particles govern the electrical conductivity, because collisions of charged particles restrict their movement under the action of any impressed electric field, for example, $E_0$. The presence of a magnetic field greatly complicates the problem, as it
restricts the motion of the charged particles across $\mathbf{B}$ and therefore, makes the conductivity anisotropic. Hence, several different conductivities must be defined for use in the different physical situations occurring in the ionosphere, and these are defined in the following.

The current density $\mathbf{J}$ in the medium is given by

$$\mathbf{J} = N_0 \left( q_e \mathbf{v}_e + q_i \mathbf{v}_i \right)$$  \hspace{1cm} (1.9)

After substitution of $\mathbf{v}_e$ and $\mathbf{v}_i$ from corresponding equations (1.6), (1.7) and (1.8) for ions and electrons, the components of current density $\mathbf{J}$ are given by

$$\mathbf{J}_e = \frac{N_0 e c}{\mathbf{B}} \left[ \frac{v_i \Omega_e}{v_i^2 + \Omega_e^2} - \frac{v_e - \Omega_e}{v_e^2 + \Omega_e^2} \right] \mathbf{E}_0 \mathbf{e}_y$$  \hspace{1cm} (1.10a)

$$\mathbf{J}_i = \frac{N_0 e c}{\mathbf{B}} \left[ \frac{-v_i^2}{v_i^2 + \Omega_i^2} - \frac{-v_e^2}{v_e^2 + \Omega_e^2} \right] \mathbf{E}_0 \mathbf{e}_y$$  \hspace{1cm} (1.10b)

$$\mathbf{J}_i = \frac{N_0 e c}{\mathbf{B}} \left[ \frac{-v_i}{v_i^2 + \Omega_i^2} - \frac{v_e}{v_e^2 + \Omega_e^2} \right] \mathbf{E}_0 \mathbf{e}_y$$  \hspace{1cm} (1.10c)

where $e = q_i = -q_e$ is assumed and as before gyrofrequencies $\Omega_i$ and $\Omega_e$ differ in sign. These equations may be written in a somewhat more general form which permits the inclusion of $\eta$-component of electric field $\mathbf{E}_0$ as

$$\mathbf{J} = \mathbf{\sigma} \cdot \mathbf{E}_0$$  \hspace{1cm} (1.11)

where $\mathbf{\sigma}$ is conductivity tensor given by

$$\sigma = \begin{bmatrix} \sigma_1 & -\sigma_2 & 0 \\ \sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix}$$  \hspace{1cm} (1.12)
in a coordinate system whose third axis is aligned in the direction of $B$. Equations (1.10) or equations (1.11) and (1.12) determine the current that flows in presence of a known total applied electric field $E_0$. $\sigma_0$ is the longitudinal conductivity, which determines the current parallel to the magnetic lines of force and would exist for all directions in the absence of magnetic field. The conductivity $\sigma_1$ is called the 'Pedersen Conductivity' which is used to calculate the current parallel to that component of electric field which is normal to the magnetic field. $\sigma_2$ is the 'Hall conductivity' which determines the current ('Hall current') flowing in a direction perpendicular to both the electric and magnetic fields. In the $F$-region and above, $\sigma_0$ becomes very large and also

$$\sigma_0 >> \sigma_1, \sigma_2$$

(which become vanishingly small), as $\nu_e$ and $\nu_i$ are quite smaller there than $|\Omega_e|$ and $\Omega_1$. Therefore, $E_0$ cannot be maintained with any substantial component along the magnetic field lines, and hence the latter are very nearly lines of constant potentials. These conductivities, $\sigma_0$, $\sigma_1$ and $\sigma_2$ can be defined as

\begin{align*}
\sigma_0 & = \frac{N_e e c}{B} \left( \frac{\Omega_e}{\nu_e} - \frac{\Omega_e}{\nu_i} \right) \quad \text{(1.13a)} \\
\sigma_1 & = \frac{N_e e c}{B} \left( \frac{\nu_e \Omega_i - \nu_i \Omega_e}{\nu_i^2 + \Omega_i^2} - \frac{\nu_e \Omega_i}{\nu_i^2 + \Omega_i} \right) \quad \text{(1.13b)} \\
\sigma_2 & = \frac{N_i e c}{B} \left( \frac{\nu_i \Omega_i - \nu_i \Omega_e}{\nu_i^2 + \Omega_i^2} - \frac{\nu_i \Omega_i}{\nu_i^2 + \Omega_i} \right) \quad \text{(1.13c)}
\end{align*}

Since the current is strongly inhibited across the field lines, in the $F$-region and above whatever current is poured into the tube of force at one end, say in northern hemisphere,
must consequently pour out of it at opposite end in the southern hemisphere. Hence, a horizontal current system flows in a relatively thin spherical shell in the E- and D-regions.

Near the geomagnetic equator, the Cowling conductivity $\Sigma_3$ which is defined by

$$\Sigma_3 = \sigma_1 + \sigma_2^2/\sigma_1 \approx \sigma_1 \left(1 + \sigma_2^2/\sigma_1^2\right) \approx \sigma_1 \left(\frac{\sigma_2}{\sigma_1}\right)^2 \quad (1.14)$$

is the most important and is about 10 to 25 times as great as that elsewhere, within a comparatively narrow range of height near 100 Km (since $\sigma_2$ is greater than $\sigma_1$ by that factor). For this reason, it is permissible, in a first approximation, to consider that the dynamo region, near the equator, consists of a bounded slab near these heights. The dynamo e.m.f. (given by $U \times B$) varies over the surface of the earth. Therefore, a horizontal distribution of space charges is built up before the current can flow. The electric field of this horizontally distributed space charges will modify the tensor conductivity $\Sigma^\ast$ and influences the F-region. In the simple slab picture, this field has to reach that region through the intervening weakly ionized region where it may be supposed that the tensor conductivity is predominantly along the magnetic lines of force and has large amplitude, $\Sigma_0$. In the F-region, therefore, there is an e.m.f. conducted up along these lines of force from the horizontal space-charge in the E-region. This e.m.f. then produces horizontal currents in the (supposed) slab-like F-layer, as determined by the horizontal layer conductivity. These currents, acted on by the earth's magnetic field, experience forces, and the plasma
moves bodily, constituting the 'atmospheric motors'.

d) Collision Frequencies of Charged Particles:

Kicolet (1953) has given expressions for the collision frequencies of electrons with ions and with neutral particles. The collision frequency of electrons with neutral particles is given by the expression

\[ \nu_{en} = 5.4 \times 10^{-16} n_n T_e^{1/2} \]  \( \ldots(1.15a) \)

where \( n_n \) is the number density of neutral particles. The collision frequency of electrons with ions is represented by the expression

\[ \nu_{ei} = \left[ 34 + 4.18 \log \left( \frac{T_e^3}{n_e} \right) \right] n_e T_e^{-3/2} \]  \( \ldots(1.15b) \)

The electron-ion collision frequency, \( \nu_{ei} \) is much more temperature dependent than the electron-neutral collision frequency, \( \nu_{en} \). The sum of these two collision frequencies \( \nu_{ei} \) and \( \nu_{en} \) is termed as the effective electron collision frequency or simply electron collision frequency, \( \nu_e = \nu_{ei} + \nu_{en} \).

An expression for the collision frequency of ions with neutral particles is given (Chapman, 1956) as

\[ \nu_i = 2.6 \times 10^{-9} \left( n_n + N \right) M^{-1/2} \]  \( \ldots(1.16) \)

where \( M \) is the molecular weight of the ions and neutral particles, which are assumed to have the same mass. One does not need to consider ion collisions with electrons, because the electrons are so light that the ions are, essentially, not affected by encounters with electrons (although the
electrons are, of course, greatly affected by their encounters with ions, which are represented by eq.1.15b).

1.23 Importance of Equatorial Ionospheric Studies, with the Emphasis Mainly on the E- and F-Regions:

At the magnetic equator, the earth's magnetic field is totally horizontal, due to which a variety of most interesting phenomena originate in the equatorial ionosphere. One of the topics of great interest has been that of observations of density irregularities of various scale sizes. It is quite well known that most of the irregularities are generated in the equatorial ionosphere. The dip equatorial region is particularly interesting in this respect as the electric and magnetic field configurations and the electron density gradients existing there, which are difficult to obtain elsewhere, are most suited for providing simplicity to understanding of generation mechanisms of these irregularities and in turn, in giving the reasonably good explanations for associated equatorial ionospheric phenomena.

The equatorial ionospheric E- and F-regions have, over the years, provided a variety of perplexing yet interesting problems to the radio communications. The practical importance of studying the equatorial ionosphere was emphasized by the observations of radio amateurs who were able to communicate, primarily during nighttime, on frequencies near 50 MHz (far above the maximum value of plasma frequency, $\omega_p = 4\pi N_e e^2/m_e \approx 10$ MHz) between points on either side of magnetic equator (Southworth, 1960). This occurred in spite of the fact that MUF (maximum usable frequency) predictions indicated that the propagation should
be impossible. These amateur contacts which were most prevalent around the equinoxes, were aimed to see the relationship between echostructure and the rapid fading of HF radio signals, known as equatorial flutter fading which is known to be closely associated with the equatorial spread-F, an irregular phenomena occurring in F-region.

Of interest to the present work are those aspects of irregular phenomena observed within the equatorial ionosphere that manifest themselves as wavelike perturbations (irregularities) of electron densities and electric fields, when considering the transmission of radio signals to or from the ground stations and spacecrafts, for such investigations as ionospheric sounding and cosmic or ionospheric noise. These irregularities may be of a localized or resonant nature.

The lower ionospheric regions (below 1000 Km) are, in some respects, the most interesting of the whole upper atmosphere, for they support a wide range of physical phenomena than any other regions do. They are not understood in detail partly because of the complexity of their processes and partly because of observational limitations. It has been recognized that a certain feature of radar scatter returns (radar echoes) on a conventional ionogram (essentially the output of a swept frequency h.f. radar) is closely associated with changes in the equatorial magnetic field and hence the electrojet current (Matsushita, 1951). This H.F. scatter is generally called as equatorial sporadic-E ($E_{sq}$), as shown in Fig. 1.1.
Fig. 1.1. Ionogram showing sporadic-E
(After D'Angelo, 1969)
However, the real progress which has been made recently in our understanding of the physics of the scatter returns is primarily the results of the VHF and HF scatter radar observations (~50 MHz and greater) carried out in Peru (close to magnetic equator) at Jicamarca (Bowles and Cohen, 1957, 1962; Bowles et al., 1960, 1963; Cohen and Bowles, 1963a,b, 1967; Cohen et al., 1962; Balsley, 1965, 1969a,b, 1973a; Farley, 1971; Balsley and Farley, 1971, 1973; Farley and Balsley, 1972, 1973; Cohen, 1973; Fejer et al., 1973, 1975a,b). At such frequencies, most of the transmitted energy of radio waves passes through the ionosphere and is lost; only a small fraction is scattered back to the receiver from small fluctuations in the electron density. Radio signals at such frequencies which have, however, travelled the lower equatorial ionosphere uninterrupted, are found to have rapid fluctuations in amplitude and phase, causing fading of the waves. As has been pointed out already (page 21), the irregularities such as spread-F occurring in upper equatorial ionospheric regions (F-region), may be responsible for causing such variations in the HF radio signals.

a) Equatorial Electrojet (E-Region):

Observations of the enhancement of diurnal range of horizontal component H of geomagnetic field could be accounted for by the enhancement in the horizontal conductivity in the region near magnetic equator (Cowling, 1932; Martyn, 1947; Cowling and Borger, 1948). Cowling (1932) showed that the horizontal conductivity would be enhanced by postulating that
vertical Hall currents are inhibited by the polarization electric field built up in vertical direction in the conductive region where $\mathcal{V}_i/\mathcal{E}_i \gg 1$ and $\mathcal{V}_e/|\mathcal{E}_e| \ll 1$. The suppression of these vertical currents is consistent with the idea of a belt of high current density (i.e., the vertical polarization field enhances the horizontal current flow considerably) which accounts for the enhanced horizontal conductivity, in the equatorial ionosphere at E-region heights. The high concentration of electric currents flowing from west to east in a narrow belt flanking the dip equator, on the sunward hemisphere, was named the 'equatorial electrojet' by Chapman (1951).

The equatorial electrojet has been a subject of extensive study both observationally and theoretically. The in-situ rocket-borne experiments have established the vertical and latitudinal extent of the equatorial electrojet and have provided approximate values of electron and current densities. The electrojet occupying a narrow height range of 10 to 15 Kms, is centered at an altitude of about 105 Kms and it appears in the areas within two to three degrees of latitude of magnetic dip equator. The positive daytime electrojet consists of essentially a flow of electrons toward the west. The positive ions have no appreciable ordered motion because of their relatively greater mass and greater collision frequency with neutral particles in this region. This westward day-time electrojet flow reverses during nighttime and flows toward east (Balsley, 1969a,b, 1970). At night, the equatorial
E-region ionization, along with that in the D-region, tends to disappear. However, certain electron density irregularities in the electrojet region can somehow exist at night in the midst of reduced electron density.

Electrojet models based on latest evidences have been described from time to time (Maeda, 1955; Zmuda, 1960; Sugiura and Cain, 1966; Sugiura and Poros, 1969). The latest of these models is proposed by Sugiura and Poros (1969) which is necessarily idealized model. In this, they made the assumptions that the primary electrostatic field is uniform and that the vertical Hall current is completely inhibited within approximately ± 2° around the magnetic dip equator. Although these assumptions can not be true, in practice, they are certainly reasonable and necessary for the first order theory. Therefore, the use will be made of this idealized model along with the assumptions made in the present analysis of the instability theories for the equatorial electrojet region.

b) Equatorial Sporadic-E (E\\textsubscript{sq}):  

Superimposed on the normal E-layer and sometimes obscuring it in conventional ionograms, may be one, or more dense layers of ionization. Ionosonde often detects such dense layers, patches or ledges of ionization (layers of enhanced ionization) at heights of 100 - 120 km which is known as 'sporadic-E or E\textsubscript{S}' (Fig.1.1) because of their rather random appearances. Generally, E\textsubscript{S} appears as a patchy and partially transparent layer, while sometimes it appears in sheets,
which completely blankets the overlying F-layer and is known as 'blanketing' type $E_s$. While the morphology of $E_s$ has been studied almost since the beginning of systematic ionospheric observations, the theoretical approach has been extremely difficult. There is no doubt that the $E_s$ is the most irregular phenomena in the ionosphere, because of both its random appearance in time and space and its structure.

Several distinct categories of $E_s$ are now identified empirically. Some of these appear on normal days and are probably associated with the dynamic processes. Whitehead (1970a) has given an excellent summary of all types of $E_s$ (temporal, auroral and equatorial), reviewing briefly the earlier theories of formation of sporadic-E irregularities. Near the magnetic equator, a distinct type of 'equatorial $E_s$' ($E_{sq}$) is observed which is patchy and transparent to waves reflected from higher level. It is predominantly daytime phenomena and is strongly correlated with the equatorial electrojet current (Matsushita, 1951).

$E_{sq}$ occurrences are negatively correlated with the geomagnetic disturbances (Matsushita, 1957). It has been found that even on quiet days there are occasional disappearance of $E_{sq}$ for short periods associated with abnormally low values of horizontal magnetic field intensity (Matsushita, 1957; Cohen et al., 1962; Gouin and Mayaud, 1967; Rastogi et al., 1971; Krishnamurthy and Sengupta, 1972). This disappearance of $E_{sq}$ is attributed to the reversal of electrojet currents during that period and is termed as 'counter
electrojet' (Gouin and Mayaud, 1967).

The highly transparent $E_{sq}$ is now mostly attributed to a rather inhomogeneous plasma structure believed to be produced due to plasma instabilities, e.g., Two-stream and Cross-field instabilities. Transparent echoes can be accounted for due to partial reflections from either sharp gradient in electron concentration or small-scale weak irregularities occurring in the equatorial sporadic-E layer. The cross-field plasma instability is found to be responsible for some diffuse non-blanketing type $E_{sq}$ (Tsuda et al., 1966, 1969).

c) Equatorial Spread-$F$:

It is now established that F-region reveals itself in diverse forms and regular and irregular shapes on ionograms obtained from ionosondes. One of these mysterious irregular forms is a phenomenon which shows a diffuse character called 'spread-$F$' which is attributed to scattering by irregularities of ionization embedded in the surrounding region. The term 'spread-$F$' is derived from the spread, smeared or fuzzy appearance of the F-layer-reflected echo traces, seen on the ionograms; that is, the reflection of a vertically incident electromagnetic wave appears to occur at a continuum of altitudes. In common usage, the phenomenon of spread-$F$ is, generally, associated with the actual ionospheric conditions causing the spread echo traces. The gradual and vast accumulation of knowledge about the spread-$F$ for many years has, certainly, revealed that it is one of major and important ionospheric features, very useful for high frequency long
distance communications.

There are two main classes of spread-F; 'frequency-spreading' and 'range-spreading' which are shown in Fig.1.2. The high and temperate latitude ones are usually characterized by frequency-spreading type in which the frequencies of the reflected signals appear to be shifted by varying amount. At equatorial latitudes, the spread-F is mainly of the range-spreading type in which apparent variations in the reflection heights 'smear out' the traces. Basically, both types of spread-F have been described for equatorial ionospheric regions (Cohen and Bowles, 1961; Calvert and Cohen, 1961; Pitteway and Cohen 1961; Krishnamurthy and Rao 1964; Huang, 1970; Skinner and Kelleher, 1971; Nielson and Crochet, 1972).

Equatorial spread-F occurs in the evening and at night. It is most prevalent before mid-night and occurs more frequently in sunspot minimum years than sunspot maximum. A brief comparison of the characteristics of the equatorial and high latitude spread-F is shown in the Table 1.1.

Moreover, the morphology of equatorial spread-F is so different from that of high latitude spread-F and also, the experimental evidence suggests that the cause may not necessarily be the same for the spread-F in both regions. It is well-known and now believed, on the basis of correlations made between the occurrence of spread-F and other recent ionospheric observations, such as radio star scintillations and angular distribution of radiations scattered, that the phenomena of spread-F, occurring both on bottom side (Cohen
Fig. 1.2. Two types of spread-F. The upper ionogram shows the type commonly called in the equatorial region. The lower one shows the type usually observed at middle to high latitudes (After Hines et al., 1965)
Table 1.1: Characteristics of Spread-F

<table>
<thead>
<tr>
<th>Equatorial Spread-F</th>
<th>High Latitude Spread-F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Occurs within the geomagnetic latitude zone from 0° to 30°</td>
<td>First evident at latitude from 40° to 60°. Maximum occurrence occurs just above auroral zone</td>
</tr>
<tr>
<td>2. Negatively correlated with magnetic activity</td>
<td>Positively correlated with magnetic activity</td>
</tr>
<tr>
<td>3. Maximum incidence at equinoxes</td>
<td>Maximum incidence in winter</td>
</tr>
<tr>
<td>4. Occurs in the evening and night only. Most day but usually at night. Prevalent before midnight</td>
<td>Can occur throughout the day but usually at night. Most frequent between midnight and sunrise.</td>
</tr>
<tr>
<td>5. Range-spreading type</td>
<td>Frequency-spreading type</td>
</tr>
</tbody>
</table>

and Bowles, 1961) and on the top side of the layers, is caused by the magnetic field-aligned irregularities (or inhomogeneities) in electron density in the F-region.

Some of the important and burning questions in a complete theory of spread-F which need to be answered are (i) why such field-aligned irregularities cause spread-echoes (spread-F) ; (ii) how are they produced ? and (iii) how can their important observed characteristics be reasonably understood ? The specific physical processes causing the development of spread-F are not well understood. Among the proposed causes for spread-F irregularities are (i) atmospheric turbulence; (ii) convective diffusion; (iii) vertical
transport due primarily to an irregular polarization field in the E-region, which is communicated to F-region along the highly conductive lines of the geomagnetic field; (iv) hydromagnetic waves arriving from outer space; (v) charge particles' penetrations; (vi) the gravitation-induced Rayleigh-Taylor instability. A brief review on the existing theories of occurrence of spread-F irregularities has been given by Cole (1973) and Farley (1974).

1.3. Observations of Ionization Density Irregularities in the Equatorial E- and F-regions:

The equatorial ionosphere has, over the years, provided a wide variety of perplexing and yet interesting problems to radio communicators. The phenomena, occurring in equatorial ionosphere such as $E_{eq}$ spread-F, Barium cloud striations, fading of HF radio waves, radio star scintillations, fluctuations in signal strength of satellite transmissions, HF and VHF scatter, etc., are familiar manifestations of the ionization density irregularities. Therefore, the study of the irregularities generated in the equatorial ionosphere has been a scientific endeavour for several decades. A great deal of effort, both experimentally and theoretically, has gone into investigating these ionospheric E- and F-region irregularities for last one and half decade or so.

During recent years, experimental studies of the equatorial E- and F-regions made by a variety of ground-based and space techniques have revealed the presence of an assortment of irregularities in electron density under a wide variety of circumstances and over a wide range of wavelengths.
These observations have shown the existence of several types of the irregularities, based on their scale sizes, shapes, spectral measurements and other characteristics which depend upon the local conditions and other important parameters of ionospheric regions of interest such as electron density, electric fields and plasma streaming velocity.

In order to clarify the objective of the present studies, we first present the important observed results of the electron density irregularities in both the equatorial E-, in particular, the electrojet and F-regions. Their types and most important features which are of interest to the present studies, will be briefly discussed in the following.

1.31 E-region Irregularities:

The presence of an anomalous scattering region in the equatorial E-region was indicated in the earliest (Circa, 1937; Berkner and Wells, 1937) low magnetic latitude ionosonde records. Examination of some of the features of this region seen on the ionosonde records and now in recent rocket and radar observations, clearly indicate that the equatorial E-region is embedded with both the weak and strong electron density irregularities (i.e., small and large amplitude fluctuations in ionization density). During the last decade or so, the equatorial E-region irregularities, particularly the equatorial electrojet irregularities have been becoming increasingly well described by radar and in-situ rocket studies.

It is now certain that much of our elucidation and understanding of the physical processes responsible for the generation of the equatorial E-region irregularities depends upon the VHF radar and in-situ rocket observations. From these observations, it is well established that these irregularities are mostly associated with the electrojet region, a range that agreed well with the limits of the electrojet current system determined by Singer et al. (1951). Although their main characteristic features are now well known and have been briefly reviewed by Farley (1974), for the sake of totality of the studies concerned here we shall draw below an overall picture of the important characteristics of the electrojet electron density irregularities of our present interest.

There are various kinds of electron density irregularities observed in the equatorial electrojet (Balsley, 1969b; Prakash et al., 1973) which are all highly elongated along
the earth's magnetic field (Bowles and Cohen, 1957; Egan, 1960). On the basis of the spectral observations of VHF radar echoes returned from the irregularities, there are two distinct types of irregularities in the electrojet; type I irregularities (Bowles et al., 1963; Cohen and Bowles, 1963a,b, 1967; Balsley, 1969a,b) and type II irregularities (Balsley, 1969b). The echoes returned from these two groups are classified as type I and type II echoes respectively. The major characteristics of these types of irregularities in context to the present studies are briefly enumerated as follows (Balsley, 1969b, 1973a, Fejer et al., 1973, 1975a,b).

a) **Type I Irregularities:**

Type I irregularities are those which are thought to be directly excited, at the observed wavelengths, by the two-stream instability in a collisional plasma (Farley, 1963a,b; Buneman, 1963). They are distinguished from the other types by the following observed characteristics.

1. These irregularities are produced when the relative electron-ion drift velocity (i.e., streaming velocity of electrons) is large enough and exceeds the threshold velocity which is ion-acoustic velocity (supersonic) in the electrojet (approximately equal to 360 m/sec.).

2. These are plane-wave structures. The lines of force of earth's magnetic field are always very nearly in the plane of the waves. The deviation is seldom more than 1°, i.e., they are highly field-aligned (Bowles and Cohen, 1957; Egan, 1960).

3. They only appear when the electrojet current exceeds some minimum value. Threshold for echoes at 148 MHz (corresponding
to 1 meter wavelength irregularities) is somewhat higher than the threshold for echoes at 50 MHz (3 meter wavelength). That is, threshold is higher for smaller wavelength which means that strong current is required for the formation of such irregularities.

4. Type I irregularities travel in directions most nearly parallel to the directions of mean flow of electrons. They have a relatively constant Doppler shift corresponding approximately to ion-acoustic speed in the medium, i.e., they travel with the phase velocity $V_p$, equal to the ion-acoustic speed $C_s$, in marginally stable state in the electrojet.

5. They are generated during day and at times at night.

6. Type I echo strength, i.e., the irregularity amplitude generally varies as electrojet current strength which varies with altitude. But however, they have a nearly constant amplitude between 15 and 1 m wavelengths (Prakash et al., 1973).

7. When they occur, they propagate in a wide range of angles, including $90^\circ$ (vertical incidence), relative to the horizontal, at wavelengths as short as 1 meter, i.e., type I echoes appear more or less simultaneously over a substantial range of radar elevation angles.

8. These have a narrow, sharp and nearly marginally stable spectrum, with a distinct maximum at a constant Doppler shift that corresponds at least approximately to $C_s$ of the medium, which is independent of the elevation angles of radar beam, and is symmetrical about zero Doppler shift (i.e., about $C_s$).
9. Type I spectral strength does not correlate at all with the increase or decrease in magnetic field strength as seen on the ground-based magnetometer records and therefore presumable with the electron drift velocity (Cohen and Bowles, 1967).

10. It was pointed out by Balsley (1973b) that in consistent with some of VHF backscatter radar observations, small wavelength (e.g., 3 m) type I irregularities do in fact propagate in the form of isolated wave-packets with soliton shaped envelopes (fairly sharp isolated pulses). The evidence for such features was also reported in earlier experimental works (Balsley, 1969b; Farley and Balsley, 1973).

11. Very recently, Fejer et al. (1975a,b) have reported that the type I are observed only in the upper portion of the electrojet, above about 104 km. Their spectral shape vary strongly with altitude (Cohen, 1973, Balsley and Farley, 1973), especially when the electron drift velocities, \( V_p \), are large and the scattering from the irregularities is strong. No echoes were observed during daytime a few kilometers above the height (\( \sim 107 \) km) of maximum type I power.

12. At times they exhibit slight spectral asymmetry in the east-west plane (Fejer et al., 1975a).

13. The maximum \( V_p \) is observed at the height which is 4 km above the height predicted on the basis of the electrojet models of Sugiura and Cain (1966) and Sugiura and Poros (1969). Sometimes, fairly large and fast variations in \( V_p \) of the type I irregularities are also observed (Fejer et al., 1975a).
14. The upgoing type I waves reach a larger amplitude than the
down going waves (Fejer et al., 1973).

b) **Type II Irregularities:**

They are generally considered to be generated due to a
gradient drift instability (Simon, 1963; Hoh, 1963; Register
and D'Angelo, 1970 and references therein) and can be easily
excited than type I, for wavelengths longer than a few meters
(> 10 m). The following are the major features of the type II
irregularities in view of the present interest.

1. These irregularities, having smaller (3-15 meter) and larger
(30-300 meters and more) scale sizes, are observed even when the
mean $V_D$ is quite small and below $C_s$ (subsonic), whereas 1 meter
type II are too weak to be detected. In fact, this class is
never observed at the equator for wavelength of 1 meter or less.

2. These are practically always present, during both the day
and night times, at least at long wavelengths, and at short
wavelengths when type I are absent.

3. They have a rather much broader spectrum, with the variable
width often greater than the mean Doppler shift which is
approximately proportional to the cosine of elevation angle.

4. These are generally weaker and have a variable smaller mean
Doppler shift which is greater for echoes returned at more
oblique angles.

5. They propagate at all angles, including 90°, relative to the
horizontal, with the electron drift velocities. Although the
mean motion is, generally, in horizontal directions, their
'broad frequency spread (broader spectrum) about the mean Doppler
shift indicates that they are not just drifting horizontally at some particular velocity, but rather that the motion is more complex.

6. Drift velocities of these irregularities range from 50 m/sec. to at least 360 m/sec. (Balsley, 1969a,b). For velocities above 360 m/sec, the spectra become contaminated by type I Echoes, showing the appearance of type I only. But at times, however, the type II spectra also show the velocities greater than 360 m/sec (the ion-acoustic speed), when the type I contamination is least (Balsley, 1969b; Cohen, 1973). Type II irregularities in the electrojet can, therefore, exist independently of the type I which means that type II can not arise from type I as postulated by Dougherty and Parley (1967).

7. During nighttime they travel eastward (Balsley, 1969a,b) in contrast to their daytime westward motion (Balsley, 1966), implying a close relation between type II irregularity motion and the electron flow obtained from dynamo theory of electrojet. Drift of these irregularities reverses, during both evening and morning hours, at the time that is reversal time of $V_D$, showing that the electron drift velocity and type II irregularity drift are zero at nearly the same time. Therefore these features along with those of (6) lead to conclude the fact that the type II drift velocity is linearly related to the true electron drift velocity (Balsley, 1967; 1969b; Pejer et al., 1975a,b).

8. They exhibit roughly isotropic structure of east-west/vertical velocity distribution of the random velocity components (i.e., those components which contribute to the
spreading about the mean drift velocity) (Balsley, 1969b).

9. Type II echo power is proportional to the square of the type II drift velocity (Balsley, 1969b).

10. A marked splitting (bifurcation) of the echoing region occurs at times well away from midday, when the electrojet intensity (i.e., $V_D$) is considerably much less than its normal midday value when the type I are produced (Bowles and Cohen, 1962; Balsley, 1965, 1969b; Fejer et al., 1975b). This implies that the type II are the only ones present when the electrojet is bifurcated; the type I appearing only when the two layers are well merged.

11. The irregularities appear only near the top and bottom edges of the electrojet under marginal conditions (Balsley, 1969b).

Radar observations (Balsley and Farley, 1971), at 16.25 and 49.92 MHz, corresponding to 10 and 3 meters irregularity wavelengths respectively, revealed that the enhanced backscatter return is a mixture of type I and type II. The type II irregularity amplitude falls off rapidly with the increasing backscatter radar frequency, so that enhanced backscatters at 146.25 MHz (1 meter wavelength) only have a type I spectrum with a definite threshold $V_D$. They (in 1973) further reported that (a) the spectra of the irregularities are usually still smeared and sometimes have two distinct peaks, showing the fact that the long wavelength irregularities are present; (b) the velocities corresponding to the spectral peaks at higher altitudes can be of the order of 100-200 m/sec, horizontal and
vertical ones being comparable (Cohen and Bowles, 1967); (c) the fading times or lifetimes of the echoes in the lower region (below 105 km) are of the order of 0.03 sec or longer, and in the upper layer, the lifetimes are much shorter, often less than 0.01 sec.

Very recently, Fejer et al., (1973, 1975a,b) report the Jicamarca radar observations taken at a frequency of 49.92 MHz and deduce from them the following features of the irregularities. The phase velocity of the obliquely travelling waves varies drastically with the altitude and the velocity is very small in the lowest part of echoing region and then increases with height. The Doppler shift (phase velocity) and the irregularity strength vary rapidly in time at a given altitude and can even change sign (Balsley and Parley, 1973). During the day, echoes are observed only in a narrow altitude region about 20 kms wide (between 93 and 113 kms) with a single maximum in the echo strength at approximately 103 km, but sometimes, the maximum being at altitudes as low as 100 kms. At night, the echoes exhibit strongly layered structures and are concentrated in many (sometimes five or more) discrete thin layers, which can be at altitudes as high as 130 kms. The altitude of echoing region(s) changes when the electrojet reverses an hour or two after sunset (reversal time was found to be 2048 hr), i.e., there was an interchange in the altitudes of the echoing regions. The nighttime echoes can sometimes be nearly as strong as those observed during the day, even though the nighttime electron densities are 1-2 orders of magnitude smaller. When the electrojet is strong
the observations show highly variable type I (as well as type II) echoes with both positive and negative Doppler shifts.

c) **In-Situ Rocket Irregularity Observations:**

With the advent of rocket and satellites, a new dimension has been added to the scope of radar observations discussed above. Using in-situ rocket-borne Langmuir (Prakash and Subbaraya, 1967) and resonance (Prakash et al., 1972) probes, many important characteristics of ionization density irregularities have been, further, obtained. While in-situ results support the radio and radar observations to some extent, many new exciting and important features have been revealed. We shall now briefly outline below the important properties and characteristics of those equatorial E-region irregularities which are of interest to our present studies, based on in-situ rocket observations at Thumba, India (Prakash et al., 1969, 1970, 1971a,b, 1972, 1973). Prakash et al. (1973) have recently summarized their rocket-borne measurements, and based on their scale sizes or spectral analysis (or both) and other characteristics, they have classified the irregularities into following types:

1. **Larger Scale, Type L. Irregularities:**

These irregularities have larger scale sizes of a few kilometers in the vertical direction and more than 40 kms in the east-west (horizontal) direction. These are observed only during nighttime flight (Prakash et al., 1970). The large scale structures of the irregularities are very prominently observed in the height regions of 90 to 130 kms. The ionization density
in these structures is found to vary by a factor lying between 4 and 25, thereby giving them the appearance of distinct layers. These are found to appear randomly and in the form of discrete bursts in the regions of density profile which shows a large downward (negative) gradient (Fig. 2.2), while the regions with an upward (positive) gradient are smooth and almost free of irregularities.

2. **Medium Scale, Type M, Irregularities:**

They have scale sizes ranging from 30 to 300 meters and can be classified into following types:

i) **Type M:** These irregularities, with scale sizes in the range of 30-300 meters, are observed only in the regions where the background electron density profile exhibits a positive gradient (density increasing with height) during daytime and evening twilight hours and a negative gradient during nighttime (Fig. 2.2). They have amplitudes varying from a few percent to about 30 percent. From radar observations, these are identified as type II irregularities. They are observed in altitude region of about 90 to 130 km. During daytime, these have large amplitudes (more than 20 percent) around 85 km. The amplitudes decrease with increasing height, reaching a value of about 5 percent around 95 km and showing a rapid decrease above about 95 km. During nighttime also, the irregularities with amplitudes as large as 30 percent are observed, but however, they are confined to an extended height region from 90 to 130 km. During evening hours, these are observed both in 85 to 100 km and 140 km regions, though the amplitudes
in the upper region, are smaller.

The amplitude and the size of the irregularities are found to decrease with increase in electron density. They are found to have a definite shape in the medium and exhibit a saw-tooth type structure, with a steeper rise than fall in electron density during the ascent of the rocket and with a steeper fall than rise during the descent of the rocket. On an average, as one moves along the directions of the positive gradients, the increase in the electron density is sharper than decrease.

ii) Type Ms: These irregularities have small amplitudes (only a few percent) and are observed to occur along with type Ss which are described below.

3. Smaller Scale, Type S, Irregularities:

The type S irregularities with amplitudes varying from 0.1\% to a few percent, have scale sizes lying between 1 and 15 meters, and can be categorized into following types:

i) Type Sc: This type of irregularities with the scale sizes in the range of 1-15 meters, is observed to occur in the same height region where type Mc (with amplitudes as high as 30 percent) are produced, but with much smaller amplitudes (from 0.1 percent to a few percent). They occur in the form of discrete bursts and the amplitudes of the higher scale sizes are greater than those of lower scale sizes. Using a power law, \( E(k) = ck^\alpha \) (where \( E \) is the power in wave number \( k \) and \( c \) is a constant), these are found to have a large scatter in spectral indices.
(the spectral index \( n \) being \(-4\) below 100 kms and \(-3\) in the 110-140 kms region during evening time, between \(-2\) and \(-4\) around 90 kms during daytime and \(-4\) around 95 kms and \(-3\) around 120 kms during nighttime). Because of their occurrence on most of the rocket flights and their observed steep spectra in contrast to the type I flatter spectrum, the type Ss are identified as type II irregularities.

ii) Type Ss: They occur nearly continuously during midday only, in the altitude region of 100-120 kms where \( V_{D} \) is higher, with a peak intensity (maximum amplitude which is of the order of 1-2 percent) near 105 km. Even though the type Ss occur in the same scale sizes as type Sc, their nature is quite different. They are observed in all scale sizes ranging from 1 to 15 meters with nearly a constant amplitude at a given altitude and have a flat spectrum with spectral index zero, which is consistent with the flat type I spectrum observed at 16, 49.92 and 146.25 MHz (Balsley and Parley, 1971). Unlike type Sc (i.e., short wavelength type II), their amplitudes show no correlation with the electron density profile. The amplitudes of the irregularities are found to increase with the detector frequency. Based on the comparison between the profiles of the type Ss irregularity amplitudes and the profile of the electrojet current (Sastry, 1970) with a maximum around 105 km, the type Ss have been identified as type I irregularities.

1.32 F-Region Irregularities:

The irregularities in the equatorial F-region have been studied extensively by various workers over several decades,
since they were first observed with ionosonde measurements by Berkner and Wells in 1934. Till to-day, using a wide variety of observational techniques, several types of irregularities, such as large scale irregularities or large patches (~ several hundred kilometers in size), small scale field aligned irregularities (scale sizes ranging from a few meters to several kilometers) and travelling ionospheric disturbances (tens of kilometer and more in size), have been reported in the literature. Of these, small scale irregularities (scale sizes of the order of a few kilometers down to a few meters) are most intensively investigated and are, however, of fundamental importance to the phenomena of spread-F, first detected by Booker and Wells (1938). Larger patches (Large scale irregularities) are, in actuality, a collection of small scale irregularities, and spread-F will be seen as long as the patch is over an observing station. These irregularities have been thought to be manifestations of spread-F and therefore, the equatorial spread-F has been attributed to the irregularities (or inhomogeneities) in electron concentration (or density) in the F-region of the equatorial ionosphere.

Experimental observations on equatorial spread-F irregularities are obtained employing various techniques, e.g., ground-based ionosondes (a review on recent ionosonde work has been given by Rastogi, 1973), HF and VHF back-scatter as well as forward-scatter radars (Farley et al., 1970; Woodman, 1973), in-situ rocket-and satellite-borne probes (a review by Kelley, 1973), scintillations of satellite radio transmissions (Huang, 1970; Wernik and Liu, 1973; Argus et al., 1973), radio star
scintillation records (Koster, 1963), etc. Herman (1966) and Glemesha and Wright (1966) have comprehensively reviewed the earlier experimental observations on spread-F irregularities. The other reviews of work on spread-F irregularities and their associated phenomena have also been given by Kent and Wright (1968), Kent (1970), King (1970) and Nielsen and Crochet (1972). Farley et al. (1970) have, recently, given a critical review on the VHF backscatter radar observations of equatorial spread-F irregularities and brought out difficulties that existing theories have in explaining many of the observations. Recent observations with HF and VHF backscatter radar (Farley et al., 1970; Kelleher and Skinner, 1971; Kelleher and Rottger, 1972; Woodman, 1972, 1973; Balsley et al., 1972), in-situ rocket-and satellite measurements (Hanson and Sanatani, 1971; Hanson et al., 1972, 1973; McClure, 1973; McClure and Hanson, 1973; Dyson, 1971, 1973; Kelley, 1973; Dyson et al., 1974; Kelley et al., 1975) and other measurements like scintillations, have revealed a vast amount of new informations about the equatorial spread-F irregularities and their characteristics.

Although very recently, Farley (1974) has summarized their most important basic characteristics, we shall in the following catalogue those features which are mostly related to the interest of our present studies, made in the thesis: (1) The spread-F irregularities are highly field-aligned ionization density irregularities (Spencer (1955) who seems to have been first in suggesting such field-alignment); (2) They are mainly
observed only at night (Martyn, 1959). They have never been observed during the day except that at times they may persist for a short period after sunrise (Farley et al., 1970); (3) Most of the irregularities have generally wavelike structures with both the 'noiselike' and the 'sinusoidal' appearances (McClure, 1973; Dyson et al., 1974). However, sometimes coherent non-sinusoidal structures of the irregularities are also observed (McClure, 1973; Dyson et al., 1974; Kelley et al., 1975); (4) The wavelengths are observed more or less simultaneously in a range from a few meters (\sim 3\ m) or less (\lambda_\perp < \rho_\perp\ ion\ Larmor\ radius) to a few kilometers (\sim 20\ kms) or more (\lambda_\perp >> \rho_\perp) transverse to the magnetic field. Scintillation observations (Koster, 1963; Huang, 1970; Wernik and Liu, 1973) show that the most effective wavelengths are of the order of 200-300 m; (5) Generally, the irregularity amplitude is very nearly proportional to the irregularity scale size over the range 70 m to 7 km, i.e., the gradient in ion concentration are independent of wavelength (Dyson et al., 1974). In this wavelength range, they observed their power spectrum to be often approximately proportional to k^-2 (k is wave number); (6) The irregularity amplitudes are observed in the range from 0.01 - .03 percent to less than 0.1 percent relative to the background electron density. However, at times they have amplitudes comparable to the largest auroral amplitude values. There are evidences that 'sinusoidal' structures with wavelengths from approximately 1 to 20 kms and peak-to-peak amplitudes from \sim 50\ percent\ down\ to\ 0.01
percent are also observed (McClure, 1973; Dyson et al., 1974; Kelley et al., 1975); (7) Field-aligned irregularities usually appear in rather large patches; that is, when the irregularity structures do appear and are well developed, an extended region of the ionosphere is affected. This extent in the east-west direction has been observed from 100-400 meters to 1000 kms (Cohen and Bowles, 1961; Clemesha, 1964), in the north-south upto 1000 kms (Koster, 1963) and in vertical direction to heights a few hundred kilometers above 1000 kms (Woodman, 1972, 1973). The thickness of the patches appears to vary from 10-200 kms (Calvert and Cohen, 1961; Yerukhimov, 1962); (8) The irregularities are observed to have often very sharply (thin) layered structures (Woodman, 1972, 1973) as well as coherent, steepened wavelike structures (Dyson et al., 1974; Kelley et al., 1975) exhibiting an asymmetric east-west gradient on either side of the irregularity patch observed at HF frequencies, but more symmetric at the higher frequencies (Nielson and Crochet, 1972; Kelley et al., 1975); (9) The irregularities occur over a wide range of altitudes from as low as 250 kms to 1000 kms (well above the F2 layer peak) at times. They are most often observed below F2 peak (bottomside or underside of the layer) and are identified as bottomside spread-F. They can appear essentially simultaneously above, below and at the peak (Farley et al., 1970; Woodman, 1972, 1973; Balsley et al., 1972); (10) They usually appear first within an hour or two after sunset, only when the F-region is fairly very high and moving upward and
minimum threshold altitude (\( \sim 300 \) km or more) exists which the bottom of the layer must lie above. At times they are generated almost anywhere in the F-region, no matter which way the region is moving. They persist often for several hours as the layer moves downward and then are eventually quenched. In a period before sunrise when the electron densities are small, they are also observed even if the layer is at fairly low altitudes (Farley et al., 1970; Woodman, 1972, 1973; Balsley et al., 1972); (11) The drift velocities of the irregularities are comparable to those of F-layer. Their drifts range from 10 to 500 m/sec. The most probable speed is 60-100 m/sec. The drift direction is predominantly east-west (Kelleher and Rottger, 1972), being east by day and west by night, and north-south component is zero (Cohen and Bowles, 1961; Calvert and Cohen, 1961). The vertical drift velocities often are 100 m/sec (3 to 4 times greater than that of normal undisturbed region) with mean downward velocity being \( \sim 25 \) m/sec and the mean upward velocity being as large as 50-60 m/sec, whereas the mean eastward velocity is \( \sim 110 \) m/sec (Balsley and Woodman, 1969; McClure and Woodman, 1972; Balsley and Haerendel, 1972; Rottger, 1972), implying that the drift velocity varies rapidly with the altitudes. Small(weak) perturbations are observed to travel with an apparent slower speed than the large (strong) perturbations which produce strong echoes returning from the regions close to F-region peak (Farley et al., 1970); (12) Growth times of the irregularities range from a few seconds or less to a few tens of minutes (\( \sim 30 \) min) or more (Farley et al., 1970; Kelley et al., 1975); (13) Basically, for equatorial
regions, two types; (a) a range-spreading occurring mainly before midnight and (b) a frequency-spreading occurring later in the night, have been observed (see sec. 1.23a). Recent VHF radar studies indicate, further, that there may be two (or even more) different classes for each type of spread-$F$ irregularities, at short wavelength at least, just as there are two types (Type I and Type II - sec. 1.31a and b) of E-region irregularities. One class of F-region irregularities is weak and produces a very narrow Doppler spectrum (Farley et al., 1970), whereas the second corresponds to much stronger spread-$F$ echoes, with a wide spectrum and the turbulent drift velocities (electric fields) with fluctuations larger than their mean (Balsley et al., 1972).

These density irregularities which serve as a means of studying the ionospheric plasma, have also been observed and investigated by artificial means, for example, in artificially generated ion plasma clouds related at the equatorial E- and F-region heights (Rieger, 1969, 1971, Haerendel et al., 1970; Davis and Moore, 1970; Davis and Althouse, 1970; Davis, 1971; Valenzuela et al., 1973; Raghavarao et al., 1976), in a reflex arc plasma produced in the laboratory (Hooper, 1970; Hooper and Girvin, 1971) and in other recent laboratory experiments simulating the certain essential characteristics of the equatorial electrojet (D'Angelo et al., 1974, 1975; John and Saxena, 1975a,b, 1976a,b; Saxena and John, 1975). The observations of local conditions favouring the formation of the field-aligned striations (irregularities) in the plasma clouds and in the laboratory experiments, and the study of
their observed features, such as growth, spectrum, propagation, scale sizes, evolution, etc., provide a valuable source of information regarding the nature of ionospheric irregularities. Such observations are quite helpful and provide a better insight into the understanding more clearly of the source (instability) mechanisms which are responsible for the generation of the irregularities described above.

By virtue of their observed features, dispersion characteristics and the conditions of their occurrence, these artificially created irregularities have been identified as the naturally occurring Type I (D'Angelo et al., 1974; 1975; John and Saxena, 1975a, 1976b) and Type II (Davis and Moore, 1970; Davis and Althouse, 1970; Davis, 1971; Hooper, 1970; Hooper and Girvin, 1971; Ogawa, 1972; Saxena and John, 1975; John and Saxena, 1976b) irregularities. In view of the present studies, the author is interested in understanding the instability mechanisms which could explain the formation of naturally occurring ionospheric irregularities. We will not therefore, be describing the observations of artificially produced irregularities.

1.4 Possible Instability Mechanisms Associated with the Eand F-Region Irregularities:

The main concern of the work done in this thesis is a theoretical study most relevant to the above-mentioned plasmawave irregularities of ionization density occurring in equatorial ionosphere. In recent years, although a large quantity of observational data of these irregularities have been accumulated and a substantial theoretical research has
been advanced in accounting their production and many of the observed features, there are a few other important basic characteristics whose explanation is still uncertain and the detailed agreement between the theory and these observations is not wholly established. Therefore, more theoretical work is further needed as suitable theories are not yet developed. The difficulty lies in the fact that so many parameters exist in the study of ionospheric plasma that it becomes very much cumbersome to consider them all simultaneously. Because of this complexity, it is almost likely that there are many different physical processes (instability mechanisms) which may be responsible, individually or collectively, for the occurrence of ionospheric irregularities.

In the preceding section, we laid out the observational features and properties of the density irregularities. Now we turn our attention to the investigation of the sources of their origin. It is now certain that the ionospheric irregularities have been identified as some kinds of waves or oscillations or fluctuations or perturbations occurring in ionospheric plasma. The ionospheric plasma which is, as has already been mentioned, a weakly ionized inhomogeneous plasma embedded in orthogonal d.c. electric and magnetic fields (at the equator), can become unstable against self excitation of a large variety of waves and natural modes of oscillations. At any frequency, these oscillations or fluctuations can, in general, be grouped into two classes: essentially the electromagnetic transverse modes and the electrostatic longitudinal modes which are
somewhat like sound waves (acoustic waves). While both these types of modes, appearing as plane wave irregularities, may be present in the E-and F-regions, there are experimental evidences that the irregularities are, in general, of electrostatic types because the longitudinal electrostatic waves which exist only in matter, are most sensitive to the properties of plasma. The electrostatic modes, therefore, represent the principal subject of interest of our present studies and will, thus, be explored in the present theoretical investigation made in the following chapters. However, we shall restrict ourselves to those perturbations (i.e., modes of oscillations) which occur only in the ionization density, as these are more relevant to the observations of ionospheric irregularities.

The source of the origin of these density fluctuations (waves) may, naturally, be identified with one of the plasma instabilities or more than one operating simultaneously. Several instability mechanisms, by a number of workers, have been suggested so far, as the source of the above-discussed different types of irregularities, e.g., Type I and Type II in E-region and F-region irregularities. A number of reviews has been given by various authors on the instability theories of equatorial E-region irregularities (Whitehead, 1970a; Kato, 1972; Tsuda, 1973; Farley, 1974) and of equatorial spread-F irregularities (Farley et al., 1970; Cole, 1973; Farley, 1974). As being the most successful mechanisms for the origin of the irregularities concerned, the instabilities
which have attracted considerable interest soon after they were proposed to be operating in the ionosphere and have been most extensively investigated theoretically by several workers, are classified, according to their source of driving energy, mainly, into three kinds: (i) The Cross-Field ($E \times B$) or Gradient-Drift instability; (ii) The Two-Stream instability, both being applied to E-region and (iii) The Gravitation-induced Rayleigh-Taylor instability having relevance to F-region. These all are generally low frequency instabilities, the frequency of oscillations, $\omega$, being less than or comparable with the ion cyclotron frequency, $\Omega_i$ (sometimes $\omega$ may have values greater than $\Omega_i$, for example, in the case of two-stream instability). An attempt has been made here to present the theoretical treatment of these three kinds of low frequency electrostatic instabilities, in both linear and nonlinear regimes, which are capable of giving rise to growing irregularities and appear to explain satisfactorily some of their important basic features observed during both day and night time in the E- and F-regions of equatorial ionosphere.

It is not intended that this chapter should outline the development of existing theories of the instabilities just mentioned, especially within the context of ionospheric irregularities, but rather that it should at least provide, for reasons of completeness, basic need and unity, their specific physical mechanisms describing how they are produced in terms of basic plasma physics concepts. The theories of these instabilities will be briefly reviewed and discussed
in the different chapters of the thesis (Chapters II, III and IV). However, a physical description on how the instabilities operate, is necessary to study the properties of modes (irregularities). Therefore, before concluding this chapter, we shall give below the definitions and a pictorial view of these three instabilities to have a physical insight into their driving mechanisms and to understand their formation, in the equatorial ionospheric regions of interest.

a) **The Cross-Field or Gradient-Drift Instability:**

In the presence of orthogonal d.c. electric and magnetic fields, an inhomogeneous weakly ionized plasma, such as equatorial ionospheric plasma, is subject to an electrostatic instability commonly called 'Gradient-drift instability' if there exists an appreciable gradient in plasma density. While the name 'gradient-drift' is assigned because of the fact that the charged particles drifts are involved in the instability excitation in presence of density gradient acting as the energy source of the instability, it has also been known as 'Cross-Field (or $\mathbf{E} \times \mathbf{B}$) instability' (because the crossed electric and magnetic fields act as driving forces of the instability) or 'Drift-resistive instability' (because of an important role played by the neutral particles in the form of collisions with the charged particles, giving rise to finite resistivity). The instability produces, in general, low frequency electrostatic charge density oscillations having characteristic drift frequency, $\omega$ small compared with $\Omega_i$. These waves propagate in a direction essentially normal to $\mathbf{B}_0$. 

with the phase velocity \( v_p(\omega/k) \) which coincides with the drift velocity of the plasma particles caused due to the combined effects of pressure gradient and electric field with \( E_0 \). This instability, under specific suitable conditions, can give rise to the growing irregularities in ionization density that are aligned along the direction of magnetic field.

The basic physical picture of this instability of the charge density perturbation can be understood on the basis of Rosenbluth-Longmire picture taking into account the fact that the ions and electrons do not drift equally in crossed electric and magnetic fields when finite resistivity is included (Rosenbluth and Longmire, 1957). One of the modes in which this instability can operate has been given by Tsuda et al. (1966), Sato and Tsuda (1967), Reid (1968), Sato et al. (1968), and McDonald et al. (1975) for E-region and by Williams and Weinstock (1970) for F-region and is illustrated here in the Fig.1.3. Its mechanism is solely due to the difference between electron and ion mobilities versus neutral particles. Suppose that the steady background density gradient, \( \gamma n_0 \) and an applied d.c. electric field, \( E_0 \), both acting vertically upward (in x-direction) exist, together with the ambient magnetic field, \( B_0 \), directed into the paper (in z-direction), as shown in Fig.1.3. The horizontal line represents an unperturbed contour of constant electron concentration. If now the density is perturbed by small-amplitude sinusoidal (a plane wave) variation with wave-front parallel to the z-x plane, the \( E_0 \times B_0 \) drifts of the ions and electrons will
Fig. 1.3. Simplified schematic physical picture showing irregularity formation process. Secondary polarization fields $\mathbf{E}$ (solid arrows) and the magnetic field $\mathbf{B}$ force the ionization along the vertical directions (broken arrows), causing the density fluctuation shown to enhance if the background density increases with increasing $x$(height).
make them move to the left (in y-direction). Since the Hall mobility of the ions is always less than that of electrons, the medium will be polarized. The space charges will then appear as a result of the electron and ion density profiles being somewhat out of phase, which in turn, gives rise to small scale secondary polarization electric fields, $\mathbf{E}$ as shown by solid curves in Fig. 1.3. Since the intensity of induced (polarization) electric fields depends upon the charge density, their direction reverses alternately at intervals of half-wavelength of fluctuations. This polarization field $\mathbf{E}$, again operating with $\mathbf{B}_0$, causes the charged particles in enhanced regions (crests) to $\mathbf{E} \times \mathbf{B}_0$ drift downwards and in the depleted regions (troughs) upwards depending on whether they are immersed in dense or dilute ambient plasma. Thus the density perturbation develops getting enhanced in the region of crests and reduced at the troughs, so that the mode is unstable and appears to grow in amplitude, making clearer contrast against the background density.

One can easily realize from the picture that if either the electric field, $\mathbf{E}_0$ or the density gradient, $\nabla n_0$ were reversed in direction, the perturbations would tend to disappear, giving rise to stable situation. Thus the perturbations amplify in amplitude only when the electric field, $\mathbf{E}_0$ and the background density, $\nabla n_0$ are appreciable and in proper directions. For small amplitude waves, the effect of classical diffusion counteracts this growth process (amplification) so that there exists a certain threshold of
instability beyond which the diffusion is not sufficient to smooth out the disturbance.

In Fig. 1.3, we have demonstrated a mere schematic representation of the case when $E_0$ is directed straight upward so that the difference of the ion and electron Hall mobilities is important. Similarly, we can have another mode operation of the gradient-drift instability even when the applied electric field is directed toward right (in $y$-direction) instead of upward, but then the difference of the ion and electron Pedersen mobilities is more important. And their opposite directions now tend to produce a similar periodic space-charge potential which leads to similar results. But, however, this latter mode generates larger wavelength irregularities at greater altitudes in the ionosphere than the former mode (Reid, 1968).

b) **Two-Stream Instability:**

The two-stream instability is perhaps the most extensively investigated in plasma physics and appears to be the first plasma instability to be treated theoretically and/or observed experimentally. It can certainly be traced back at least 25 years (Bohm and Gross, 1949) and with some generosity all the way back to Langmuir in 1925 (which is the year zero in plasma physics calendar). If the plasma contains particles with directed energy due, for example, to the electron drift velocity (giving rise to the electron streaming) of the current carrying electrons, another electrostatic instability, namely the two-stream instability,
can be excited. When the current (or drift velocity) reaches a certain threshold level, the plasma becomes unstable and strong electrostatic type waves with phase-fronts aligned with the magnetic field are generated by the excitation of the two-stream instability (Buneman, 1959).

In general, the two-stream instability develops due to the interaction of two groups of plasma particles drifting with respect to each other. This instability leads to growing longitudinal electrostatic waves, which derive their energy from the kinetic energy associated with the relative drift velocity of the particles (i.e., relative electron streaming). These waves which are high frequency oscillations with frequency, $\omega$, greater or equal to $\omega_i$ and have smaller wavelengths compared to those produced by the gradient-drift instability, are of mainly two types: electron oscillations at a frequency of the order of $\omega_p$, excited when the drift velocities of the electron ($V_D$) relative to the ions exceeds the mean electron thermal velocity ($V_e$); and ion-acoustic oscillations at about $\omega_{pi}$ when $V_e > V_D > C_s$ (where $C_s$ is the ion-acoustic speed). The first type is excited with $V_p = V_D$; while the second one with $V_p = C_s$ (slightly greater than the mean thermal velocity of ions), and the latter have smaller growth rates (Buneman, 1959).

In the equatorial electrojet, one of such conditions on the electron drift velocity, namely $V_D > C_s$ is easily satisfied at least during the day time. Such longitudinal ion-acoustic electrostatic plasma waves mentioned above can,
therefore, be excited in the electrojet by the two-stream instability driven due to cross-field streaming electrons relative to ions. These smaller wavelengths waves growing in amplitude, propagate in the direction exactly normal to earth's magnetic field and are those which manifest themselves as the ionization density irregularities associated with Type I backscatter echoes (as shown independently by Farley (1963a,b) and Buneman (1963).

The two-stream instability which is also known as 'Farley-Buneman instability' as they first developed it independently for equatorial electrojet, has had considerable success and has been well received as a possible mechanism for the formation of Type I irregularities. Basically, its physical mechanism describing how it operates, is similar to that of cross-field instability just discussed, with the difference that there is no vertical density gradient in the present case of the two-stream instability and is briefly described below.

We know that the equatorial electrojet is characterized by magnetized electrons ($\gamma_e \ll \omega_e$) and collisional ions ($\gamma_i \gg \omega_i$). The crossed ambient vertical polarization electric field and the horizontal (south-north) earth's magnetic field then lead to a cross-field streaming of electrons with respect to ions in y-direction (Fig.1.3) as the ions are tied up with the neutrals because they are highly collisional. Suppose that the horizontal density interface is perturbed by a small amplitude plane wave
(sinusoidal) oscillation as shown in Fig. 1.3, the secondary polarization electric field $\tilde{E}$ is then produced, alternately in directions at the interval of half wavelengths because of the phase difference between electron and ion density profiles which arises due to the ions lagging behind the electrons as the ions are much heavier than the electrons. This secondary field $\tilde{E}$ crossed with $B_0$ makes crests (troughs) of the perturbation to move downwards (upwards). Now if initially, the magnitude of relative electron-ion streaming drift velocity is greater than $C_s$, the given perturbations become unstable and in turn, they will continue to grow in amplitudes giving rise to a form of spectrum of longitudinal electrostatic plane waves, called ion-acoustic waves, with wave-front parallel to ambient magnetic field.

c) Rayleigh-Taylor Instability:

It is well known that an interface dividing the heavy incompressible fluid on the top from the supporting lighter incompressible fluid at the bottom in a gravitational force field, is unstable. Such an instability is called Rayleigh-Taylor (R-T) instability investigated first by Rayleigh (1916) for the case of hydrodynamic fluids. This instability is, in fact, the fundamental magnetohydrodynamic instability of an incompressible fluid interface experiencing an acceleration, $g$ which may be due to either real gravitational force or equivalent effective gravitational force due to different plasma configurations (Chandrasekhar, 1961).
In analogy with this instability of a fluid interface, the plasma interfaces in different given plasma situations also become unstable to the small amplitude perturbations. For example, in the situation where the plasma (regarded as heavy fluid) is supported against gravity by the magnetic field (lighter fluid), the plasma-vacuum interface is one which is unstable. In another example, which is of our interest, the plasma-plasma interface in the situation where an inhomogeneous incompressible plasma is supported against gravity by a magnetic field, is prone to this R-T instability. In this latter situation, the upper plasma region with higher density above the interface can be regarded as the heavy fluid, while the lower region with smaller density below the interface as the lighter fluid, thereby fulfilling the R-T instability criteria.

In the ionosphere, a number of competing processes, such as production, recombination, and transport of electrons and ions, exist. These processes cause the ionosphere to form a layer (e.g., a layer in the F-region) whose underside has a positive density gradient and hence fulfills broadly the light fluid-supporting-heavy fluid description and therefore, is susceptible to the instabilities of R-T type. The physical description of how the R-T instability operates or is driven in the plasma situation of our interest, can be understood, on the basis of following two principles.

1) Drift Analysis: This instability is physically understandable on the basis of guiding centre motions of ions and electrons. The mechanism is essentially the charge separation
caused by the gravitational drifts of ions and electrons arising due to the effect of gravity, \( \mathbf{g} \) and the magnetic field, \( \mathbf{B} \). The charge separation so produced, which in turn, results in a polarization electric field, is able to overcome exactly the restraining influence of the magnetic field.

To understand how the instability is, basically, caused, consider the situation depicted schematically in Fig.1.4, where an incompressible inhomogeneous plasma with density increasing in the direction opposite to the direction of gravitational force, is supported against a z-directed gravitational force \( (\mathbf{g} = -\hat{z}g) \) by a x-directed magnetic field \( (\mathbf{B}_x = \hat{x}B) \). Imagine that the plasma-plasma interface (a solid horizontal line) is perturbed by a small-amplitude electrostatic plane-wave perturbation as shown in Fig.1.4.

The ions and electrons initially drift parallel to y-axis as a result of \( \mathbf{g} \) and \( \mathbf{B}_o \), with the drift velocities,

\[

\nu_d^y = \frac{m_i}{m_e} \frac{\mathbf{g} \times \mathbf{B}}{B^2} \tag{1.17}

\]

Since the drift velocity is inversely proportional to the charge-to-mass ratio, the ions and electrons will have drift in opposite directions and the ions have a velocity that is \( m_i/m_e \) times greater than the electrons. Thus the ions drift from the electrons, both getting accumulated on the interface and consequently, a charge separation is developed, resulting in a space-charge potential and hence an electric field \( \mathbf{E}' \), as shown in Fig.1.4. Now the ions and electrons will drift in the z-direction as a result of this electric field \( \mathbf{E}' \) and the magnetic field \( \mathbf{B} \) with the velocity, \( \nu_d = \mathbf{cE}' \times \mathbf{B}/B^2 \). The ions
Fig. 1.4. Simplified schematic physical view of perturbation of the plasma-plasma interface region in an inhomogeneous incompressible plasma supported against gravity $g$ by a magnetic field $B$, showing the development of the charge separation electric field $E'$ caused by the $g \times B$ drift motion.
and electrons, because of this drift, move in such a way so as to increase the amplitude of the initial perturbation and thereby, making the system unstable as the perturbation grows.

ii.) Energy Analysis: The energy principle determines whether or not a given plasma equilibrium is stable (or unstable) as a function of equilibrium parameters, but in general it does not give information about the growth rates of the instability or the plasma motion associated with it. Thermodynamically, an isolated system is unstable if, after applying a small perturbation, there exists a state of lower potential. The system itself will seek out, if possible, the lowest potential energy. As a consequence of conservation of energy, the extra energy goes into the kinetic energy of the instability. Hence such a plasma system will be unstable.

Now consider an ionosphere layer, in particular the underside of the F-layer, at a given time as sketched in Fig.1.5. Suppose an arbitrary small amplitude perturbation is introduced, as shown by the dotted line in the figure, to the underside of the F-layer in the ionosphere. To know the stability of the layer, one has to find out whether the system has increased or decreased its total energy. The difference in total energy is, essentially, due to interchange of fluid marked 1 with the fluid marked 2 in the Fig.1.5. Since the interchange is taking place in a direction parallel to both gravity and pressure force, the perturbed ionosphere will have a lower energy and hence the original configuration
Fig. 1.5. Sketch of ionospheric F-layer showing possibility for instability.
is unstable.

Of course, the energy-conservation arguments for instability to occur, are valid if the system is isolated and this is, in general, not the case here due to presence of production and recombination. Intuitively, it is then expected that the growth rate of such an instability must be able to compete with the recombination rate in order that instability should prevail.

1.5 Statement of the Present Work:

The prime goal of the investigation presented in the thesis is to make a detailed theoretical study of the above-discussed three instabilities which seem to have relevance to the subject of equatorial ionospheric plasma and hence, to the density irregularities observed during both day and night time conditions in the E- and F-regions. Waves (irregularities) under certain specific conditions discussed in the preceding sections, grow both with distance traversed and time. Conditions for the occurrence of such unstable modes, and their characteristics, such as the phase velocities, frequencies, amplitudes, structures, etc., are some of the major points in the investigation of the instabilities. Since the irregularities with a broad range of amplitude, wavelengths, etc., are observed under a wide variety of circumstances, both the linear and nonlinear theories of the instabilities have been developed in the thesis so as to account for most of the observational features.
There has been a considerable progress in the linear analysis of the instabilities in last decade or so. However, the linear analysis can predict only the existence or non-existence of the instability without a description of its subsequent development. Also it can yield only the critical (threshold) conditions on the parameters which are either responsible for the onset of the instability or related to the characteristic properties of the instability. Although many observational aspects of laboratory plasma, ionospheric irregularities and plasma cloud experiments in the ionosphere are brought into light on the basis of the linear dispersion relation, it fails to decide the ultimate fate of an initial perturbation which grows indefinitely in amplitude in the linear limit. One essentially demands that the wave amplitude should not grow indefinitely so as to have some stable configuration of the system.

It is widely recognized that the unstable plasma in nature is destined to result into after a long time of development, a state known as turbulent or nonlinear state arising due to preponderances of various unstable modes under different conditions, in which the energy supply to a plasma system may be in harmony with energy dissipation from it. This limits the amplitude of indefinitely growing perturbation as a result of some damping mechanism operating, which enables the wave to get saturated at some finite value of amplitude. The nonlinear treatment of the instability is thus mandatory so as to decide an appropriate instability saturation mechanism which can yield the informations about the saturation level of
the amplitude, frequency shift of the finite modes which grow linearly above the critical point and later saturate at some finite amplitudes. The nonlinear analysis is not only helpful in the study of long time behaviour of the instability, but it can also unravel many new basic phenomena which can never be recognized at the linear stage. This should clearly provide us with a clearer understanding of the existence and the basic mechanisms of the irregularities and some of their observed features. In this thesis the author has, therefore, tried to make a modest attempt on the nonlinear theories of the instabilities concerned.

Since the analytical treatment of the 'full nonlinear' development is too difficult to handle due to complexities both in the physical as well as mathematical concepts, our attention will be devoted mainly to the case of weak nonlinearity in which the assumption of sufficiently small amplitude perturbation can be made, in consistent with the observed amplitudes of the irregularities. With this assumption, the terms of the order higher than cube of the amplitude of the perturbation are considered negligibly small in the nonlinear set of ordinary and differential equations describing the unstable modes.

A plasma and its dynamics can be described in many possible ways. In the fluid approach which is valid when the collision mean free-path of the particles is small compared with the macroscopic scale lengths involved, the plasma can be treated as being composed of an electron-fluid interpenetrated by an ion-fluid (i.e., as two-fluid model).
The macroscopic lengths in this study are the wavelengths of perturbations. We shall, therefore, use the two-fluid model as the basis of our studies in the following chapters.

The author starts with the investigation of the gradient-drift or Gross-field instability in Chapter II, which is the potential candidate, as is widely accepted, for type II irregularities in the E-region. This study was, in fact, completed a long time ago with a primary objective to consider the effect of both the primary horizontal (E\textsubscript{Oy}) and vertical polarization (E\textsubscript{Ox}) electric field together, which was not taken into account by any earlier workers. The present study has included, for the first time, the combined effects of E\textsubscript{Ox} and E\textsubscript{Oy} through an approximate relation E\textsubscript{Ox} = \frac{\sigma_2}{\sigma_1} E\textsubscript{Oy}, which is valid for equatorial ionosphere. Furthermore, the treatment of the theory has been more general because it includes the propagation of the waves in the vertical direction also.

The characteristics of the irregularities, such as the growth rate (\omega), the minimum unstable wavelength (\lambda\textsubscript{min}), etc., for a number of situations prevailing in the ionospheric region of interest and their variation with altitude have been studied in detail. The dependence of \omega\textsubscript{1} and \lambda\textsubscript{min} on the variations in the horizontal electric field, background electron density and the background density gradient is investigated. The author also discusses the importance of vertical polarization field in the formation of smaller wavelength and fastest growing irregularities. The theoretical results so obtained, are then applied to the equatorial E-region of the ionosphere by considering an observed electron
density profile. The chapter ends with the comparison of results of the theory with the observations of Type II irregularities associated with the Type II backscatter echoes in the equatorial E-region.

In the third chapter, the author discusses a special class of coherent, weakly, nonlinear Type I modes in the equatorial electrojet, which are believed to be excited by two-stream instability. Introducing a dimensionless independent variable \( \xi \) in the wave frame, the partial differential equations describing one-dimensional Type I modes are converted into an ordinary differential equation. Having retained the quasilinear modification of \( B_{ox} \) (which provides quasilinear saturation mechanism) and ion viscosity, an amplitude dependent nonlinear dispersion relation for such nonlinear modes is found for weak nonlinearity. A study of the stability of these nonlinear modes against long wavelength, slowly varying amplitude perturbations is carried out both analytically and numerically.

We have made further investigation in support of our analytical calculations by solving numerically the exact set of basic nonlinear equations of Type I modes which otherwise, are intractable by conventional analytical methods. It is very encouraging that there is a reasonable agreement between the analytical and numerical results. This is also interesting to note that these results seem to explain the existence as well as some of the observed features of Type I irregularities associated with Type I backscatter in the equatorial electrojet.
Low frequency incompressible waves in the equatorial F-region, that seem to be responsible for equatorial spread-F, are studied in Chapter IV. In this chapter, the author has made an investigation of the nonlinear evolution of the gravitation-induced Rayleigh-Taylor instability which may be one of the possible mechanisms for the generation of equatorial spread-F irregularities.

Following the method similar to one that is described in chapter III, and including the finite Larmor radius (FLR) corrections, we have looked for a stabilization mechanism for Rayleigh-Taylor modes. The finite larmor radius corrections are found to be responsible for the existence of nonlinearity in the wave-equation and therefore, may have an important role to play in connection with nonlinear interactions of waves. The existence of coherent, weakly nonlinear, almost sinusoidal stationary solutions of the nonlinear equations describing R-T modes has thus been investigated. The final structure of the R-T modes and the shapes in which these would travel in the F-region are discussed in details. Finally, the theoretical results obtained in this chapter are also compared with the observations of equatorial spread-F irregularities made by in-situ rocket and satellite measurements.

The principal results of the investigations presented in this thesis are then summarized in the last chapter. It also includes discussion on the relevance of the theoretical studies made in the thesis to the experimental observations...
of the ionization irregularities occurring in the equatorial E- and F-regions of the ionosphere. In addition, a short investigation has been made to explain how the instability mechanism discussed here, can also support the formation of equatorial sporadic E(E_{sq}), the disappearance of E_{sq} with sudden decrease in the magnetic field value and their correlation with the equatorial electrojet and the equatorial spread-F. Lastly, the limitation of the work and the scope for further work have also been discussed.