Plasma instabilities in the equatorial E and F region Ionosphere

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Abstract: The earth's ionosphere is in a plasma state with ionization caused by solar UV and X rays. The equatorial low latitude ionosphere has many unique features. Due to combined effects of atmospheric electric field, geomagnetic field and wind dynamo the plasma density in the topside ionosphere shows instabilities such as sporadic e and spread F. These instabilities are discussed with the physical mechanism.

Keywords: Ionosphere, plasma , instabilities, ionospheric irregularities.

1. Introduction:

Our planet earth has an atmosphere which extends up to about 80-90 km. Based on chemical compositions or temperature or on the dominant physical properties we have different parts of the atmosphere with different nomenclature. The solar UV and X-rays interact strongly with the upper atmosphere and ionizes the atoms and molecules present there. This region is named as ionosphere which has no upper boundary but merges in to the heliosphere. The matter in the ionosphere is in the plasma state. The ionosphere plays an important role in radio communication system by reflecting radio waves in the broadcast band. Due to variations in the atmospheric neutral composition and the production rate with altitude, the plasma density in the ionosphere is vertically stratified in to D, E and F layers. Each layer is controlled by different physical processes and has different dominating ions. In the D and E regions the main ions are O_2^+, N^+_2, NO^+ and dominated by photochemistry. The ionization is caused mainly by the UV and X-rays in the D region and solar radiation of EUV wavelength is responsible for E region. The F layer is usually subdivided into three layers. The lowest region (F_1) is produced by photoionization and loss process take place by recombination with electrons. The next layer is the F_2 layer where maximum electron density occurs. The uppermost part of the ionosphere above F_2 layer is usually termed as topside ionosphere where ionization is dominated by diffusion. These processes occur during the daytime i.e. in the sunlit side of the earth. During nighttime, ionization occurs in the E region only due to the resonantly scattered sunlight and star light. The ionosphere shows significant variations with time of the day, latitude, longitude, altitude, season, solar activity, geomagnetic activity and eclipses. Owing to the geometry of the earth's dipolar magnetic field lines a distinctive latitudinal characteristics is found in the ionosphere. So the ionosphere is classified into three latitude regions, low (equatorial), middle and high (auroral) latitude regions. Each latitudinal region is controlled by different physical processes.

The equatorial and low latitude ionosphere has been studied by many ground and space based experiments as it has many unique features which are not found elsewhere. During the daytime one of the most prominent features seen at the equatorial low latitude ionosphere, is the Equatorial Ionization Anomaly (EIA) or the Appleton anomaly (Appleton, 1946). It is distinguished as a depression in plasma density or trough at the geomagnetic equator and two peaks at about $\pm 10^o$ to $\pm 15^o$ magnetic latitudes. The EIA is formed as a consequence of E×B upward plasma drifts associated with the eastward electric field (E) and a northward horizontal magnetic field (B). As the plasma is lifted to greater heights, it diffuses downward along the geomagnetic field lines due to the gravitational force and plasma pressure gradient. And this results in ionization enhancements on both sides of the magnetic equator. This physical phenomenon is generally termed as the plasma fountain. The fountain rises to several hundred kilometers at the magnetic equator and the crests become weaker with increasing altitudes. At higher altitudes a single peak appears over the magnetic equator. In situ measurement of plasma density in the F region ionosphere provides useful information about the location of the EIA, its spatial and temporal extent and variability with season and solar cycle.

The ionospheric electric field plays a dominant role in low-latitude electrodynamics. The ionospheric plasma is always in motion due to the effects of electric field, neutral wind etc. As it is not at a thermo-equilibrium state, there arise various kinds of instabilities in the ionosphere. To reach in to its thermo-equilibrium state, the plasma emits some of its energy in the form of some wave mode. So we can say that plasma instability is a process in which free energy of plasma grows in a collective way. These instabilities create fluctuations in the ionospheric plasma density which is termed as irregularities. The ionospheric irregularities may be categorised in to two processes viz. E region (Sporadic E) and F region (Equatorial spread F) instability process. In this paper we are going to discuss some aspects of these two features observed in the ionosphere.

2. Plasma instabilities responsible for ionospheric irregularities:

Let us now see hoe instabilities arise in the E and F region ionosphere. There are three instabilities which are responsible for some of the natural phenomena of ionosphere.

I. **Two stream instability**: The two stream instability is important in the electrojets which flow in the ionospheric E region at both low and high latitudes. When streams of electrons and ions flow with different velocities an electrostatic wave will produce. These waves propagate nearly perpendicular to the magnetic field.

II. **The wind shear theory**: The horizontal winds in the neutral air in the E region suggest a large vertical velocity gradient of plasma density. Whitehead (1960) has developed the shear theory according to which the velocity gradient or velocity shear redistributes the E region ionization and leads to the formation of sporadic E layers. The shear depends on the vertical motion of ionization which occurs due to horizontal motion of wind across the magnetic field. An idealized illustration of wind shear mechanism in E region is shown in Figure 1. The plane of the diagram represents an east – west vertical plane at the magnetic equator. The ions are dragged by the horizontal winds and deflected by the magnetic field. For which the collision frequency exceeds the gyrofrequency, so that $\nu_i > \omega_i$. The ions experience a Lorentz force (L×B) and are driven at an angle to the wind velocity, so that they accumulate within the shear. But the electron are unaffected by the neutral wind since $\nu_e < \omega_e$ and are constrained to move along the magnetic field lines. The electrons move in such a way that they neutralise the charges set up by the ion motion. So the layer accumulated within the shear consists of neutral ionization.

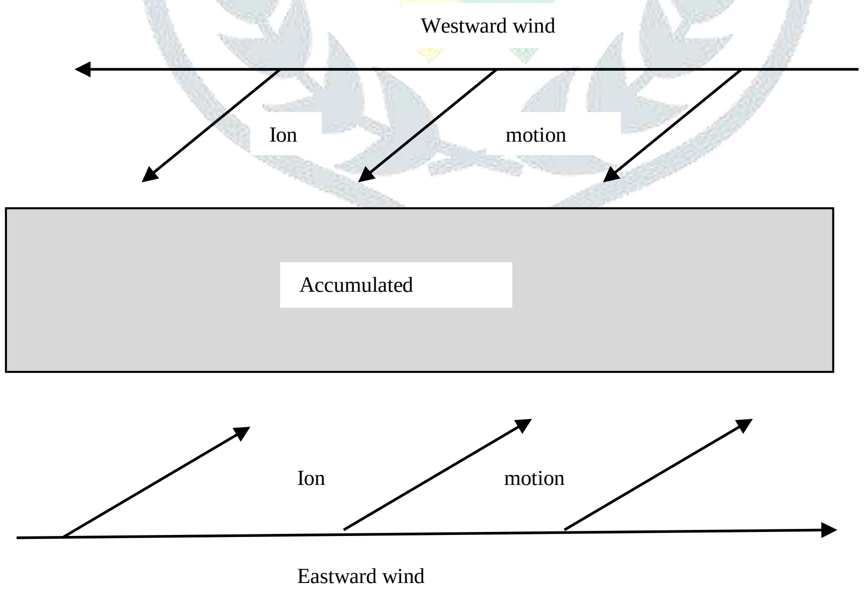

Figure 1: Illustration wind shear theory

III. **Gradient drift instability**: This mechanism is an example of Rayleigh – Taylor instability, which have a property of reduction of total energy by interchanging two elements of a fluid. The R-T instabilities are basically driven by gravity and on occasions assisted by other forces like zonal and vertical component of neutral winds (Kelley and McClure, 1981; Raghavarao et al., 1987). The R-T instability enables a chain of irregularities to succeed resulting in generation of wide spectrum of irregularities (Sridharan et al., 2012). An illustration of this mechanism is shown in figure 2. In the figure an enhancement of plasma density is shown in the X-Z plane, with a reduction of density in the Y direction. A force which may be neutral wind of gravity acts from one side and it is assumed that a small kink is appeared spontaneously in the contours of constant plasma density. Then the plasma density in the edges of the enhancement slightly varies in the X direction. The positive ions and negative electrons move in opposite direction as they are acted upon by the force perpendicular to the magnetic force. This motion combined with the variation of plasma density creates a small polarization electric field E_p leaving net positive and negative charges as shown. Now there will be an additional force $E_p \times B$ acting either Y or – Y direction. This stabilizes the kink on the top side but increases it on the bottom side. The term gradient drift is often called as E × B drift which is responsible many anomalous behaviours shown in low latitude ionosphere such as Equatorial Ionization Anomaly, Plasma fountain, Plasma bubble (electron density vacuum within the ionosphere) etc.

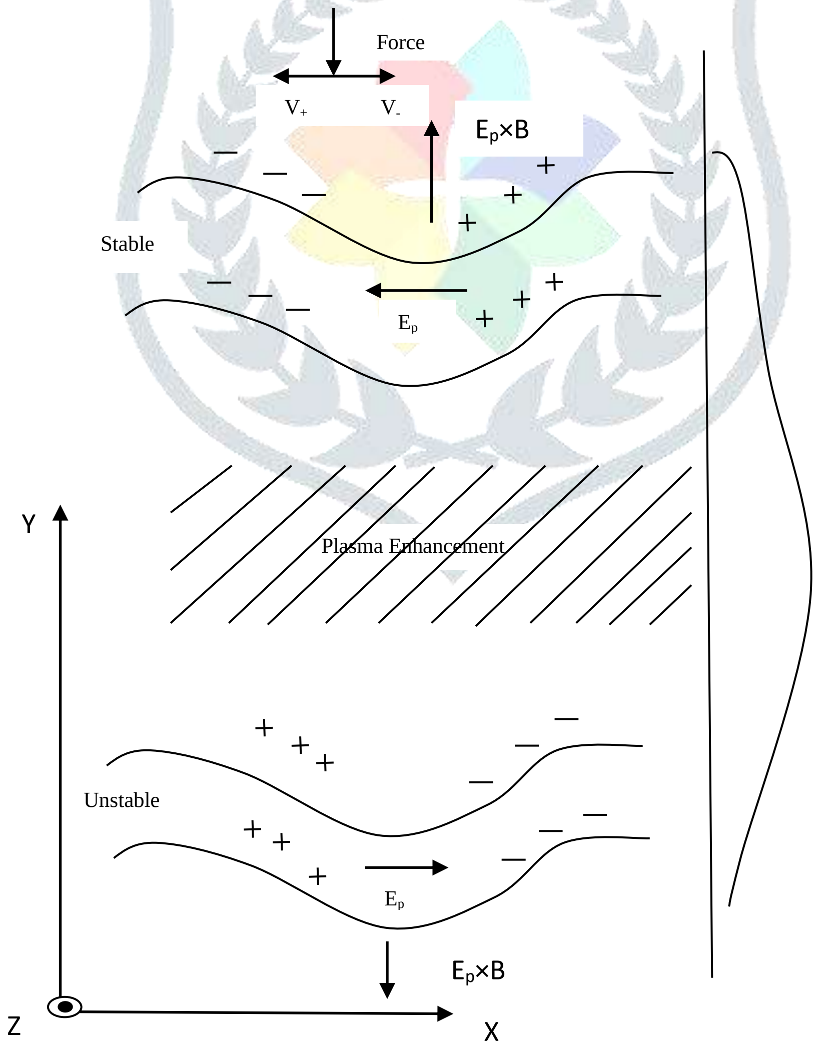

Figure 2: Illustration of Gradient drift instability

3. E region irregularities:

There are substantial ambient electric fields in the ionosphere. At low and mid latitudes these electric fields are produced by the dynamo action of neutral winds driving the charged particles across the earth's magnetic field through collisional interactions. In polar regions the electric fields are generated primarily through interactions between the magnetosphere and solar wind and are transmitted downward along the highly conducting magnetic field lines. These electric fields generate a worldwide current system which flow primarily in the E region ionosphere at altitudes of 100-120 km. These currents are intense in particular two regions – the magnetic equator where magnetic conductivity is unusually high along perpendicular direction of the magnetic field. And the second one is the auroral zone where electric fields are perpendicular to magnetic field. In both regions the large currents lead to plasma instabilities which generate ionospheric plasma density perturbation.

In the E region ionosphere most of the irregularities are due to the anomalous behaviour of E region which is termed as sporadic-E (Es). On ionograms, the sporadic E is seen as an echo at constant height which extends to a higher frequency than is usual for the E layer. The characteristics of the sporadic E for equatorial, mid latitudes and polar regions are distinguishable from each other. Near the equator, sporadic E is basically of two types – equatorial type sporadic E [Es-q] and the blanketing type sporadic E [Es-b].

Due to tidal motion a current system is generated which is known as the Sq current system in the E region. This current system results in an eastward electric field at low latitudes. In the equatorial E-region the east-west electric field drives the equatorial electrojet (Fejer, 1981), which is a narrowband of enhanced eastward current flowing in 100 to 120 km altitude region within ± 3º latitude of magnetic equator during daytime. The Es-q occurs due to the equatorial electrojet with a maximum near noon in its diurnal variations. On the other hand the Es-b occurs during the period of weak or counter electrojet (Chandra and Rastogi, 1975). The other causes that can influence in the formation of sporadic E layer are thunderstorms, meteors etc. The occurrence of equatorial sporadic E (Es-q) can be explained by the gradient instability theory (Ecklund et al., 1981) which will be discussed in a later section separately.

The physics behind the formation of Es in the mid latitude is due to wind shear theory. The sporadic E layer is a non uniform and wavy thin sheet of enhanced plasma density. The ionospheric plasma in a large volume is swept in to a thin layer to form a sporadic E layer. As explained by Whitehead 1960, Es layer appears as a result of the combined effect of wind shears of tides and gravity waves in the upper atmosphere. Also some long lived metal ions are swept from the lower atmosphere by vertical shear of horizontal wind due to combined effect of ion – neutral collisions and B×V drift of plasma. In the auroral latitudes Es layer is considered to be formed due to the precipitation of charged particles, where it is a nighttime phenomenon.

4. F region irregularities:

The F region irregularities of ionosphere are commonly named as the spread F which can be detected in the ionograms as a spread in radio echo from F region. It has been explained in various reports that spread F occurs due to presence of thick range of plasma density irregularities which can vary from few centimetres to few hundred kilometres. (Farley et al., 1970; Fejer and Kelly, 1980; Ossakow, 1981). The spread F can occur at any latitudes, however the probability of occurrence is highest at equatorial and low latitudes. The spread F which occurs at the equatorial F region is called the equatorial spread F (ESF). Spread F occurrence is positively correlated with magnetic disturbance at high latitudes but negatively correlated at low latitudes.

The prime mechanism for growth of irregularities in the F region is the Rayleigh – Taylor instability (Costa and Kelly, 1978).In the equatorial region the magnetic field is horizontal and parallel to the earth's surface. The electric field in E-region is eastward during daytime. It can cause the E×B vertical drift that results in transportation of plasma upwards in the F-region. Near sunset, strength of the E-region dynamo decreases. However, at this local time a dynamo develops in the F-region which enhances the eastward electric field after sunset and intensifies the anomaly crests. After sunset, the electric field turns westwards, and the plasma drifts downwards. Thus, just before the reversal of the electric field, the field is enhanced which is called the post-sunset or pre-reversal enhancement (Rishbeth, 1971). Consequently, the vertical plasma density gradient formed at the bottom side of the F-region becomes steeper due to the rapid uplifting of the ions. This leads to generation of plasma density irregularities by the Rayleigh-Taylor instability mechanism.

As the irregularities are mapped to higher latitudes along the field lines, the latitudinal extent covered by such irregularities would depend on the altitude reached by the irregularity over the equator. Booker and Wells (1938) first suggested that the occurrence of spread F is associated with rapid post sunset rise of the equatorial F layer. It has also been noticed that when the post sunset vertical drifts at the equator are large, the necessary condition for triggering ESF is satisfied (Fejer et al., 1999; Anderson et al., 2004; Tulasi Ram et al., 2006).

5. Conclusion:

The ionosphere is a convenient place of study certain aspects of plasma physics. There are a number of plasma instabilities in the ionosphere which lead to the development of turbulent conditions. If we can achieve a full understanding of the ionospheric instabilities, there will be inevitable application to other areas of plasma physics.

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