



Planetary Ionospheres and Ionospheric Instabilities

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The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Over the several decades' degree of theoretical and experimental investigations on the Planetary ionospheres have continued to escalate in different aspects. Studying the mechanics of ionospheric events is essential to comprehending space weather, its effects on planetary atmospheres, and its instabilities. Usually, such physics entails simulating ionosphere dynamics. Ionospheric region has weak particle collision rate and weak magnetic field strength gradient. Primary Solar wind and other secondary cosmic sources are the main sources of energy and momenta to this open plasma system. These regions have many linear and nonlinear properties for the energy exchange among waves and particles. Complex radiation emission phenomena are observed in different altitudes of terrestrial ionospheric regions by ground based and satellite based observatories. In this note, characteristics of ionospheric plasma and various instabilities which are observed in this domain are discussed which are helpful for near Earth space environment.

Keywords: *Ionospheric region; planetary atmospheres; open plasma system; ionospheric plasma.*

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1. INTRODUCTION

Initially, research on ionospheric physics was focussed on origin of the ionosphere, its different layers, variability of its physical parameters with local time, latitude, seasons and on radio wave propagation. For development of experimental based observatories and theoretical frameworks, ionospheric research is mainly concern at present on dynamics of this region and on ionospheric plasma physics (Lifshitz and Pitaevskii, 2010, Rostoker and Rosenbluth, 1960, Bertrand et al., 2019, Kelley, 2009).

In 1901 after successfully transmitted radio signals across the Atlantic, G. Marconi experimentally established existence of electrically conductive layer in the upper terrestrial atmosphere and in 1902 a theoretical model on this electrically ionized media was proposed by O. Lodge. The name Ionosphere was proposed by R.A. Watson-Watt for this atmospheric conducting layer in a letter to the United Kingdom Radio Research Board (Lodge, 1902, Watson-Watt, 1929).

By using ground based and with rocket- and satellite based observatories combined with remote sensing data, pictures of planetary ionosphere were obtained for different aspects. From the Pioneer-10,-11, the voyager-1,-2, Galileo and Cassini spacecraft mission, ionospheres data of outer planets like Jupiter, Saturn, Uranus, Neptune, Saturn's moon Titan and Neptune's moon Triton were recorded by using radio occultation measurements and other spectrometric techniques. From the Mariner-10 spacecraft optical observations it was found that inner planet Mercury did not have a conventional ionosphere. In situ measurements from Venera-4 spacecraft, S-band radio occultation measurements from Mariner-5 spacecraft and other mass spectrometric measurements revealed that inner planet Venus had a well-developed ionosphere during dayside and nightside duration. With the help of Retarding Potential Analyzers (RPA) of Viking-1,-2, Phobos Spacecraft, Mars Express and Radio Science (RS) experiment of Mars Global Surveyor (MGS), suggest that ionized environment of upper atmosphere of Mars has many similarities to that of inner planet Venus (Smirnov, 2004, Schunk and Nagy, 2009, Singhal, 2009, Kivelson and Russell, 1996).

Ionospheric region acts as interface in between the lower and upper atmosphere is originated

through two major processes like photo ionization due to solar photons and impact ionization by coulomb collisions. Behaviour of this partially ionized open system is controlled by various processes and external entities like diffusion, chemical reactions, turbulences, instabilities, gradients of pressure, temperature, density, confining fields like electric and magnetic fields, solar phenomena, planetary motions and so on. Interactions among electrostatic and electromagnetic resonant and non-resonant modes with plasma particles may give different types of instabilities in this partially ionized region. In this wall less plasma system, gradients of physical parameters and in homogeneities develops for presence of input energy and momentum fluxes from diverse free energy sources in the planetary atmosphere. Due to instabilities, a non-equilibrium thermo- dynamical plasma system transits from one state to another when growth rate of instabilities become less than plasma wave frequency (Schunk and Nagy, 2009, Singhal, 2009, Kivelson and Russell, 1996, Perkins, 1978, Zolesi and Cander, 2014, Blaunstein and Plohotniuc, 2008, Takashi, 2002). Here, both large scale macroinstabilities and small scale microinstabilities are observed, but in this study we have concerned only on microinstabilities.

2. TERRESTRIAL IONOSPHERIC PLASMA

From observational data it has been found that particle density and composition vary with respect to altitudes in the Earth's ionosphere. The three major ionospheric layers are viz., the D-layer which occupies the altitude region of 50 to 90 km, the E-layer is at an altitude of 90 to 140 km and the F layer is above 140 km. The F-layer is further subdivided into two layers: F1 is above 140 to 200 km and F2 is above 200 to 400 km. Ionospheric layers are produced due to the absorption of solar radiation and characteristics of these layers stand on composition of specific constituents in these regions and respond likewise to different parts of the incident solar photon spectrum (Schunk and Nagy, 2009, Singhal, 2009, Takashi, 2002).

The low-altitude D-layer ionosphere has a charged particles density of the order of 10^3cm^{-3} . In presence of variety of negative and positive ions, negative charges of D-layer arise where most extensive positive ions are NO^+_{+2} and the cluster ion $\text{H}_3\text{O}^+ \cdot \text{H}_2\text{O}$. Primary ionization sources are 0.11nm X-rays, very intense 121.6nm

Lyman- radiation from the sun and energetic particles of cosmic rays. Charged particles density in mid-altitude E-layer is of the order of 10^5 and these charged particles are formed by solar UV radiation through photoionisation of air. Negative ions are rarely found in this region. Primary positive ions are NO^+ and $\text{O}^+_{2.}$ Decay rate of charged particles density in this region mainly take place for the recombination of electrons and molecular ions or drift motion of charged particles to lower layers of atmosphere. Physical phenomenon of aurora is observed at this region (Luhmann et al., 1996).

The high-altitude F-layer has electron density is of the order of 10^5 to 10^6 cm^{-3} . Charged particles are formed here due to solar radiation through photoionisation of atmospheric oxygen. Loss of charged particles take place for photo recombination of electrons and oxygen ions, photo attachment of electrons to oxygen atoms and drifting of charged particles to lower layers of atmosphere. F1- and F2 -layers combine together to form a single layer during night time. Aurora is observed at this altitude (Smirnov, 2004).

3. PLASMA WAVES IN THE IONOSPHERE

A variety of plasma waves are prevalent throughout the nonuniform ionospheres in presence of external fields. These plasma waves can perturb physical properties in the ionosphere. Plasma waves are electrostatic and electromagnetic in nature. Electrostatic plasma waves can have fluctuating electric fields and electromagnetic plasma waves can have both fluctuating electric and magnetic fields. Depending upon the circumstances, plasma waves can have amplitudes either small or large. These plasma waves can propagate in both unmagnetised and magnetised plasmas.

In the longitudinal mode, fluctuating electric fields are parallel to the propagation vector, whereas for a transverse mode, fluctuating electric fields are perpendicular to the propagation vector. In a magnetized plasma, plasma waves can propagate along or perpendicular or at an arbitrary angle to the direction of magnetic field. To study propagation of electrostatic plasma waves, only Gauss' law and the Poisson equation are relevant and electromagnetic plasma waves are governed by Maxwell's field equations. For electrostatic waves, plasma is affected due to perturbed charge density and for electromagnetic waves, plasma is affected

through both the charge density and the current density. Plasma waves which we are dealing with in the thesis are briefly described below (Schunk and Nagy, 2009, Singhal, 2009, Stix, 1982).

Ion sound waves: Ion sound waves are low frequency electrostatic waves which propagates in any direction in an unmagnetised plasma and along the direction of magnetic field in a magnetised plasma.

Langmuir waves: Langmuir waves are high frequency electrostatic plasma waves. These waves can propagate in any direction in an unmagnetised plasma and along the direction of magnetic field in a magnetised plasma. Ions do not take part in this high frequency wave motion and act as a stationary positive charge background.

Lower hybrid waves: Lower hybrid waves are low frequency electrostatic plasma waves and its propagation vector is perpendicular to the direction of magnetic field. Low frequency means both motion of ions and electrons are considered.

Drift waves: Drift waves are low frequency electrostatic waves supported by inhomogeneous plasma medium. These waves are known as universal instabilities in a magnetised plasma with a density gradient. These low frequency drift modes have a close phase relations with thermal particles. These modes strongly take part in wave energy exchange process called wave-particle resonance interaction.

O-modes: O-modes or ordinary waves are high frequency transverse electromagnetic plasma waves which propagates perpendicular to the direction of magnetic field. The direction of fluctuating electric field is parallel to the background magnetic field. Its electric field always lies along one axis, therefore this wave is linearly polarised and purely transverse in nature.

4. INSTABILITIES IN IONOSPHERIC PLASMA

Ionospheric plasma can be considered a natural laboratory set up for theoretical and experimental investigations on wave-wave and wave-particle interactions on various observational phenomena and instabilities to gain better understanding of the behaviour of upper atmosphere. Most of the information on various processes in the

ionosphere obtains from radio wave scattering or reflection experiments which are conducted from the surface of the earth along with through space based rocket and satellite-borne sensors. From theoretical point of view in some problems, ionospheric plasma can consider as either homogeneous or inhomogeneous medium. If plasma parameters vary little over a wavelength, ionospheric plasma is considered as homogeneous but these approximations are rarely materialized. On the other hand, due to high variations in densities, gradients in temperature and magnetic fields, corresponding ionospheric plasmas to be considered as inhomogeneous. Using the homogeneous plasma theories, it become very difficult to solve inhomogeneous plasma problems and for this, appropriate nonlinear theory is must.

There are diverse free energy sources in the Earth's atmosphere. For presence of input energy and momentum fluxes from these sources, spatial gradients of physical parameters and inhomogeneities develops, *along with* this plasma system become unstable if a small perturbation from the equilibrium state results in a growth of the perturbation. For this accumulated energy, instability is the general way of redistributing available free energy. Plasma instabilities can be treated as plasma waves which grow in amplitudes. Instabilities lead to transitions of a nonequilibrium state from some kind of one state and turbulence (Uman, 1964, Treumann and Baumjohann, 2001). Large scale macroinstabilities and small scale microinstabilities are observed in the partially ionized ionospheric plasma region (Kelley, 2004). For perturbation of local zeroth order distribution functions, microinstabilities are developed in velocity space inhomogeneities. The characteristic scale size of microinstabilities, also known as kinetic instabilities, is the order of particle inertial lengths and gyroradii. For inhomogeneities in an open system, there are many possibilities of deviations of zeroth order distribution functions and different types of microinstabilities arise. Also due to scale size of microinstabilities is small as compared with that of a plasma, it can assume plasma as homogeneous after neglecting spatial physical parameter gradient or curvature and boundaries of the system.

In the topside auroral ionosphere the ion acoustic instability takes place by electron currents or by ion beams and it exhibits a positive slope of combined equilibrium distribution function of

electrons and ions in phase space which represents resonance occurs for wave-particle interactions (Kelley, 2009, Treumann and Baumjohann, 2001).

Beam-driven instabilities are observed during active auroras and substorm conditions in auroral ionosphere and these are flowing upward from the ionosphere into the magnetosphere.

For the presence of density gradient, an universal instability also known as drift instability arises for all kinds of electrostatic and electromagnetic plasma waves in ionospheric plasma (Kelley, 2009, Treumann and Baumjohann, 2001).

For density gradients in the upper ionosphere the lower-hybrid drift instability is observed to excite lower-hybrid electrostatic plasma waves. This electromagnetic instability can treat as electrostatic instability in certain approximation and has large growth rates and important for anomalous resistivities, transport and heat conduction. Though lower-hybrid drift instability occurs in the E- and F-layers of the Earth's ionosphere for the very steep density gradients under specific circumstances; but due to high collision rates it is stabilized (Kelley, 2009, Treumann and Baumjohann, 2001).

For motion of electrons along curved magnetic field lines, gyro or synchrotron radiations are emitted which are observed in the magnetosphere and in the atmosphere of the planet Jupiter. In the magnetosphere and the auroral ionospheric plasma, Auroral Kilometric radiation (AKR) which is a nonthermal radiation is observed and it is causing through gyro-emission from trapped plasma particles. The physical mechanism of this phenomena can explain through cyclotron maser instability (Treumann and Baumjohann, 2001).

For electron density gradients and other irregularities in the low altitude ionosphere, information on plasma instabilities are obtained from equatorial spread F. In the mid-altitude ionosphere, instabilities are observed mainly in both E-and F-regions. Some of them are wind-driven thermal instabilities, Perkins instability in F-region, Kelvin-Helmholtz instability in E-region and Es-layer instability. In the high latitude ionosphere region some important investigations on generalised $E \times B$ instability, auroral electrojet instabilities and gradient drift instability are carried on (Kelley, 2019, Takashi, 2002).

5. NONLINEARITY AND TURBULENCE IN IONOSPHERIC PLASMA

As a physical system deviates weakly from its equilibrium phase with respect to space and time, it leaves linear behaviours and becomes nonlinear system. In general, a plasma is fundamentally a nonlinear medium for unstable collective modes and for energy exchange among plasma waves and particles. For fluctuations of physical parameters which are normally amplified with respect to time for instabilities, then a plasma system is in a turbulent state. Depending upon perturbation from the zeroth-order distribution function, both weak turbulence and strong turbulence are observed in nonlinear plasma (Krall and Trivelpiece, 1973, Gary, 2005, Ichimaru, 2004). In analytical treatment, a nonlinear plasma system is described by nonlinear partial differential equations and a set of algebraic expressions are obtained by using either Fourier transforms or Laplace transforms and obtain dispersion relations. To investigate theoretically on nonlinear effects, few analytical methods are used which are based on approximations and lowest order perturbation theory but absence of a general algorithm is one of its major limitations.

The first nonlinearity effect is perturbation of zeroth-order distribution function for a finite amplitude modulating plasma waves. Some of other new classes of nonlinear effects are particle trapping, BGK modes, weak particle turbulence, resonance broadening, collisionless shock waves, nonlinear Landau damping and parametric instabilities (Treumann and Baumjohann, 2001).

6. APPLICATION OF TURBULENCE WAVE-PARTICLE INTERACTION THEORY IN IONOSPHERIC PLASMA

In plasma turbulence theory roles of coupling process between non-resonant and resonant modes of fluctuations are important to sustain the stationary turbulent state. In the nonlinear regime, some collective modes and plasma turbulence saturation will occur at a later stage for nonlinear interactions. To describe such interactions analytically, Vlasov model is used in random phase approximation closure scheme (Treumann and Baumjohann, 2001, Krall and Trivelpiece, 1973, Swanson, 2012). There are three types of interactions are involved in weak turbulence theory for different and distinct physical processes

Nonlinear wave-particle interaction: Energy exchange process takes place thorough this nonlinear interaction between waves and resonant particles which are in same phase and phenomena like growth or damping of waves, instabilities, plateau or tail formation for perturbation of distribution function can occur.

Nonlinear wave-wave interaction: This interaction occurs among three normal modes only. With the help of this nonlinear interaction, it is possible to explain on diffusion of wave energy among many modes, parametric instability and dielectric properties.

Nonlinear wave-particle-wave interaction: In this interaction, particles are in constant phase relative to the beat frequency of the two waves. Nonlinear Landau damping or growth, echoes, wave scattering by particle distribution etc. can explain with this kinetic interaction.

To study collective behaviour and instabilities of collisionless plasma in velocity space regime, Vlasov equation was introduced by A. Vlasov in 1945 and L.D. Landau in 1946. Not only in plasma dynamics, this Vlasov model is applicable in different fields like from semiconductors and stellar dynamics problems to quantum mechanical problems (Bertrand et al., 2019, Swanson, 2008).

In 1976 Ronmark and Stenflo had observed that the theory of plasma turbulence could applied to the generation mechanism of high frequency plasma waves in presence of low frequency electrostatic turbulence through plasma particles and turbulent waves interaction. They had found that the growth rate became large as phase velocity of turbulent waves was nearly equal to thermal velocity of electrons. Theoretical investigation on enhanced electromagnetic wave generation in an unmagnetised plasma, due to acceleration of plasma particles by the electric field of low frequency ion acoustic waves, was carried on by Nambu and Shukla (Weiland, 2012, Deka, 1997, Ronmark and Stenflo, 1976, Nambu and Shukla, 1979, Nambu and Shukla, 1980).

7. CONCLUSION

Nonlinear wave-particle energy exchange process is one of the forefront research areas in plasma dynamics at present. Its important implications are investigated in astrophysical and in confined laboratory like tokamak plasmas by using observational data. In open nonlinear

plasma, various forms of radiation mechanisms are analyzed and characterized by nonlinear theoretical models, weak turbulence theory is one of these. On the basis of quasilinear theory, nonlinear energy exchange between resonant and non-resonant modes can explain effectively in an open system where free energy sources are available. Various low frequency turbulences are active here in presence of inhomogeneity like density gradients, temperature gradients, magnetic field gradients etc. for supply of energy and momenta from free energy sources.

Earth's ionosphere is an open system in where exotic modes-modes mechanisms are registered due to entry of input energy and momenta through primary solar radiation and other external agents. From study on these nonlinear phenomena, useful information can assemble and helpful for further improvement on knowledge of near-Earth space environment.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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