International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2025: 7.089

Analysis of Planetary Ionospheres and Their Dynamic Instabilities

M.T. Khan, M.A. Khan, I. Khan

Department of Physics, G.F. College, Shahjahanpur- 242001 (UP), India
Affiliated to S.S. University, Shahjahanpur-242001 (U.P), India
[2]Email: *drasifkhanbly[at]gmail.com*

Abstract: ***Theoretical and experimental studies of planetary ionospheres have progressively expanded over several decades in a number of different areas. A modest magnetic field strength gradient and a low particle collision rate are characteristics of the ionospheric area. The solar wind and secondary cosmic sources are the main sources of momentum and energy for this open plasma system. Numerous linear and nonlinear characteristics pertaining to the energy exchange between particles and waves are present in these areas. Both ground-based and satellite-based observatories have detected complex radiation emission events at various terrestrial ionosphere elevations. The features of ionospheric plasma and the several instabilities seen in this area are covered in this paper.***

Keywords: MHD waves, ultra-low frequency waves, solar wind velocity, Plasma Instabilities

1. Introduction

The first focus of ionospheric physics research was to comprehend the ionosphere's genesis, its multilayer structure, and the variations in physical properties with local time, latitude, and season as well as radio wave propagation. In order to establish experimental-based observatories and theoretical frameworks, ionospheric research is currently concentrated on the dynamics of this area as well as the plasma physics of the ionosphere.

O. Lodge created a reality model of the presence of the electrically conductive layer orbital shortly after G. Marconi successfully sent radio signals over the Atlantic in 1901. In 1902, Lodge announced theoretical models concerning this electrically ionized media. R.A. gave this conducting layer of the atmosphere the name Ionosphere. Watson-Watt wrote to the UK Radio Research Board [1-2].

By merging remote sensing data with ground-based, rocket-based, and satellite-based observatories, images of the planetary ionosphere for different aspects were obtained. The Pioneer-10, -11, Voyager-1, -2, Galileo, and Cassini spacecraft missions recorded the ionospheres of outer planets such as Jupiter, Saturn, Uranus, Neptune, Saturn's moon Titan, and Neptune's moon Triton using radio occultation measurements and other spectrometric techniques. Mercury's interior planet did not have a conventional ionosphere, according to optical observations made by the Mariner-10 mission [3]. S-band radio occultation measurements from the Mariner-5 spacecraft, in situ data from the Venera-4 spacecraft, and other mass spectrometric studies revealed that the interior planet Venus has a well-developed ionosphere both during the day and at nite. Viking-1, -2, Phobes Spacecraft, Mars Express, and Radio Retarding Potential Analyzers (RPA). S-band radio occultation measurements from the Mariner-5 spacecraft, in situ data from the Venera-4 spacecraft, and other mass spectrometric studies revealed that the interior planet Venus has a well-developed ionosphere both during the day and at nite [4]. The ionized environment of Mars' upper atmosphere is similar to that of Venus' inner planet in many aspects, according to the Retarding Potential Analyzers (RPA) of Viking-1, -2, Phobes Spacecraft, Mars Express, and Radio Science (RS) experiment of Mars Global Surveyor (MGS). The ionospheric zone, which serves as an interface between the upper and lower atmosphere, is created by two main processes: impact ionization from coulomb collisions and photo ionization from solar photons. Diffusion, chemical reactions, turbulence, instabilities, pressure, temperature, and density gradients, confining fields like electric and magnetic fields, solar phenomena, planetary motions, and so forth are some of the processes and external entities that control the behavior of this partially ionized open system [5].

Numerous types of instabilities may arise from interactions between electrostatic and electromagnetic resonant and non-resonant modes with plasma particles in this partially ionized region. This wall-less plasma system develops gradients of physical parameters and inhomogeneities due to input energy and momentum fluxes from different free energy sources in the planetary atmosphere. A non-equilibrium thermodynamic plasma system undergoes state changes as a result of instabilities when the growth rate of instabilities is less than the frequency of plasma waves. Both large-scale macro-instabilities and small-scale micro-instabilities are observed here, despite the fact that we have only addressed micro-instabilities in this work [6-7].

2. Ionospheric Plasma on Earth

Observational data show that the density and composition of particles in the Earth's ionosphere change with altitude. The three primary ionospheric layers are the D-layer, which is situated between 50 and 90 km above sea level, the E-layer, which is situated between 90 and 140 km above sea level, and the F layer, which is situated above 140 km. The F-layer consists of two layers: F1 is situated above 140 to 200 km, while F2 is situated above 200 to 400 km [8]. When solar radiation is absorbed, ionospheric layers are formed. These layers react similarly to different parts of the incident solar photon spectrum, and their characteristics rely on the composition of specific components in these regions.

In the low-altitude D-layer ionosphere, the density of charged particles is around 103 cm3. The D-layer's negative charges form when a variety of positive and negative ions are present. The cluster ions H_3O+, H_2O, and $NO^+{}_2$ are the most common positive ions. Ionization is mostly caused by the sun's strong 121:6 nm Lyman radiation, 0:11 nm X-rays, and energetic cosmic ray particles. Charged particle density at mid-altitude The E-layer is on the order of 105, and these charged particles are produced by solar UV radiation by photoionization of air. Negative ions are rare in this region. $O^+{}_2$ and NO^+.are the two primary positive ions [9].

The high-altitude F-layer has an electron density of 105–106 cm^3. Here, solar radiation photoionized atmospheric oxygen to produce charged particles. Charged particles are lost through photo recombination of electrons and oxygen ions, photo attachment of electrons to oxygen atoms, and drifting of charged particles to lower layers of the atmosphere. The F1- and F2-layers combine to form a single layer at nite. Auroras are visible at these elevations [10-12].

3. The Ionosphere's Plasma Waves

A variety of plasma waves are typical in the nonuniform ionospheres when there are external influences. These plasma waves may change the physical properties of the ionosphere. Plasma waves are both electrostatic and electromagnetic in nature. Whereas magnetic and electric fields can fluctuate in electromagnetic plasma waves, electric fields can fluctuate in electrostatic plasma waves. Depending on the circumstances, the amplitudes of plasma waves might be very small or very large. These plasma waves can propagate in both magnetized and unmagnetized plasmas.

In a longitudinal mode, fluctuating electric fields are parallel to the propagation vector, but in a transverse mode they are perpendicular. In a magnetized plasma, plasma waves can move along, perpendicular to, or at any angle to the direction of the magnetic field. While only Gauss' law and the Poisson equation are relevant to the study of electrostatic plasma wave propagation, Maxwell's field equations govern electromagnetic plasma waves. In the case of electromagnetic waves, plasma is caused by both the charge density and the current density [13], whereas in the case of electrostatic waves, it is caused by the disrupted charge density. The following is a quick description of plasma waves, which are the subject of this thesis:

3.1 Ion sound waves

Ion sound waves are low frequency electrostatic waves that travel along the direction of the magnetic field in a magnetized plasma and in any direction in an unmagnetized plasma [14].

3.2 Langmuir waves

Electrostatic plasma waves at high frequencies are known as Langmuir waves. In an unmagnetized plasma, these waves can travel in any direction; in a magnetized plasma, they can travel in the direction of the magnetic field. Ions function as a stationary positive charge backdrop and do not participate in this high frequency wave motion.

3.3 Lower hybrid waves

The propagation vector of lower hybrid waves, which are low frequency electrostatic plasma waves, is perpendicular to the direction of the magnetic field. Low frequency indicates that both ion and electron mobility are taken into account.

3.4 Drift waves

Low frequency electrostatic waves that are sustained by an uneven plasma medium are known as drift waves. In a magnetized plasma with a density gradient, these waves are referred to as universal instabilities. There are strong phase relationships between these low frequency drift modes and thermal particles. Wave-particle resonance interaction is a process in which these modes actively participate in the exchange of wave energy.

3.5 O-modes

High frequency transverse electromagnetic plasma waves that travel perpendicular to the direction of the magnetic field are known as O-modes, or ordinary waves. The background magnetic field and the direction of the fluctuating electric field are parallel. This wave is completely transverse and linearly polarized because its electric field is constantly oriented along a single axis.

4. Ionospheric Plasma Instabilities

In order to better understand the behavior of the upper atmosphere, ionospheric plasma can be thought of as a natural laboratory setup for theoretical and experimental studies on wave-wave and wave-particle interactions on numerous observable phenomena and instabilities. The majority of the data on different ionosphere processes comes from radio wave scattering or reflection studies carried out from the earth's surface as well as from space-based rocket and satellite-borne sensors. Ionospheric plasma can be viewed as either a homogeneous or an inhomogeneous medium from a theoretical perspective in certain situations. An ionospheric plasma is regarded as homogenous if plasma parameters fluctuate minimally over a wavelength, however these assumptions are rarely realized. Conversely, related ionospheric plasmas should be regarded as inhomogeneous due to significant differences non densities, temperature gradients, and magnetic fields. Solving inhomogeneous plasma problems becomes extremely challenging when using homogeneous plasma theories; therefore, a suitable nonlinear theory is required [15-17].

The Earth's atmosphere contains a variety of free energy sources. Spatial gradients in physical parameters and inhomogeneities arise in the presence of input energy and momentum fluxes from various sources, and the plasma system becomes unstable if a slight perturbation from the equilibrium state causes the perturbation to grow. The general method of redistributing available free energy for this accumulated energy is instability. It is possible to think of plasma instabilities as plasma waves with increasing amplitudes. Turbulence and transitions from one state to a nonequilibrium state are caused by instabilities. The partially ionized ionospheric plasma area exhibits both large-scale macroinstabilities and small-scale microinstabilities. Microinstabilities are created in velocity space inhomogeneities for perturbation of local zeroth order distribution functions. The order of particle inertial lengths and gyroradii is the typical scale size of microinstabilities, sometimes referred to as kinetic instabilities. Inhomogeneities in an open system can lead to many kinds of microinstabilities and a wide range of zeroth order distribution function deviations. Additionally, because the scale size of microinstabilities is smaller than that of a plasma, it is possible to assume that a plasma is homogeneous after disregarding the system's boundaries and spatial physical parameter gradient or curvature [18-20].

The ion acoustic instability in the topside auroral ionosphere is caused by electron currents or ion beams, and it shows a positive slope of the combined equilibrium distribution function of electrons and ions in phase space, indicating resonance for wave-particle interactions.

Beam-driven instabilities flow upward from the ionosphere into the magnetosphere during active auroras and substrom conditions in the auroral ionosphere [21].

All types of electrostatic and electromagnetic plasma waves in ionospheric plasma experience a universal instability, often referred to as drift instability, when there is a density gradient.

It has been found that the lower-hybrid drift instability stimulates lower-hybrid electrostatic plasma waves for density gradients in the upper ionosphere. This electromagnetic instability has high growth rates, is significant for anomalous resistivities, transport, and heat conduction, and can be treated as electrostatic instability in some approximations. Although lower-hybrid drift instability can exist in the Earth's ionosphere's E- and F-layers for extremely steep density gradients under some conditions, it is stabilized by high collision rates [22-23].

Gyro or synchrotron radiations, which are seen in Jupiter's magnetosphere and atmosphere, are produced as electrons move along curved magnetic field lines. Auroral Kilometric Radiation (AKR) is a nonthermal radiation that is produced by gyro-emission from trapped plasma particles in the magnetosphere and auroral ionospheric plasma. Cyclotron maser instability provides an explanation for this phenomenon's physical mechanism [24].

Equatorial spread F provides information on plasma instabilities for electron density gradients and other anomalies in the low altitude ionosphere. Instabilities are mostly seen in the E- and F-regions of the mid-altitude ionosphere. These include thermal instabilities caused by wind, Perkins instability in the F-region, Kelvin-Helmholtz instability in the E-region, and Es-layer instability. Important research on gradient drift instability, auroral electrojet instabilities, and generalized E x B instability is being conducted in the high latitude ionosphere region [25].

5. Nonlinearity and Ionospheric Plasma Turbulence

A physical system loses its linear behaviors and transforms into a nonlinear system when it slightly departs from its equilibrium phase with regard to space and time. For unstable collective modes and energy exchange between plasma waves and particles, a plasma is essentially a nonlinear medium. A plasma system is in a turbulent state when physical parameter variations, which are typically increased with respect to time for instabilities, occur. In nonlinear plasma, both weak and strong turbulence are seen, depending on the perturbation from the zeroth-order distribution function. Nonlinear partial differential equations explain a nonlinear plasma system in analytical treatment, and dispersion relations are established by applying either Laplace or Fourier transforms to a series of algebraic expressions. A few analytical techniques based on approximations and lowest order perturbation theory are used to study nonlinear effects theoretically, but one of their main drawbacks is the lack of a general procedure [26].

For finite amplitude modulating plasma waves, the initial nonlinearity effect is the perturbation of the zeroth-order distribution function. Particle entrapment, BGK modes, weak particle turbulence, resonance broadening, collisionless shock waves, nonlinear Landau damping, and parametric instabilities are a few further novel kinds of nonlinear phenomena.

6. Application of Turbulence Wave-Particle Interaction Theory in Ionospheric Plasma

The maintenance of the stationary turbulent state in plasma turbulence theory depends on the coupling process between resonant and non-resonant modes of fluctuations. Certain collective modes and plasma turbulence saturation will happen later for nonlinear interactions in the nonlinear regime. The random phase approximation closure approach uses the Vlasov model to analytically characterize such interactions. Weak turbulence theory involves three different kinds of interactions for various and unique physical processes:

5.1 Nonlinear wave-particle interaction

This nonlinear interaction between waves and resonant particles in the same phase facilitates the exchange of energy and can lead to phenomena such as wave development or damping, instabilities, plateau or tail creation for perturbation of the distribution function.

5.2 Nonlinear Wave-Wave Interaction

Only three normal modes are involved in this interaction. This nonlinear interaction can be used to explain dielectric characteristics, parametric instability, and the dispersion of wave energy among several modes.

5.3 Nonlinear Wave-Particle-Wave Interaction

Particles in this interaction are always in phase with respect to the two waves' beat frequencies. This kinetic interaction can be explained by nonlinear Landau damping or growth, echoes, wave scattering by particle distribution, etc.

A. Vlasov and L.D. Landau introduced the Vlasov equation in 1945 and 1946, respectively, to investigate the collective behavior and instabilities of collisionless plasma in the velocity space domain. This Vlasov model is useful not only in plasma dynamics but also in other domains, such as quantum mechanical problems, semiconductors, and stellar dynamics issues [27].

Ronmark and Stenflo noted in 1976 that the theory of plasma turbulence might be used to explain how plasma particles and turbulent waves interact to produce high frequency plasma waves in the presence of low frequency electrostatic turbulence. They discovered that when the phase velocity of turbulent waves approached the thermal velocity of electrons, the growth rate increased. Nambu and Shukla conducted theoretical research on improved electromagnetic wave generation in an unmagnetized plasma caused by plasma particle acceleration by the electric field of low frequency ion acoustic waves [28-29].

7. Conclusion

One of the most important areas of current research in plasma dynamics is the nonlinear wave-particle energy exchange mechanism. Using observational data, its significant consequences are examined in astrophysical and constrained laboratory settings, such as tokomak plasmas. Weak turbulence theory is one of the nonlinear theoretical models used to examine and define different types of radiation mechanisms in open nonlinear plasma. In an open system with accessible free energy sources, nonlinear energy exchange between resonant and non-resonant modes can be efficiently explained based on quasilinear theory. In the presence of inhomogeneity, such as density gradients, temperature gradients, magnetic field gradients, etc., a variety of low frequency turbulences are active in order to feed energy and momenta from free energy sources.

The intake of input energy and momenta through primary solar radiation and other external agents results in the registration of exotic modes-mode processes in the open system that is Earth's ionosphere. Research on these nonlinear processes can yield valuable data that will assist further our understanding of the near-Earth space environment.

Acknowledgements
The author is thankful to the Principal, Gandhi Faiz-E-Aam College, Shahjahanpur, Uttar Pradesh, India for providing facilities completing this work. Author is also thankful to the Chairman, Department of Physics, AMU- Aligarh for providing me the necessary facility to prepare the manuscript.

References

[1] *E.M. Lifshitz, and L.P. Pitaevskii, Physical Kinetics Vol.10: Course of Theoretical Physics, Butte*rworth-Heinemann, ISBN:978-81-8147-796-5, Reprint 2010.
[2] N. Rostoker, and M. Rosenbluth, Test particles in a completely ionized plasma, Phys.Fluids,3,1,1960.
[3] P Bertrand, D D Sarto and A Ghizzo, The Vlasov Equation 1, History and general Properties, Wiely, ISBN 978-1-78630-261-8,2019.
[4] M.C. Kelley, The Earths Ionosphere; Plasma Physics and Electrodynamics, Academic Press, Inc.ISBN: 9780120884254,2009.
[5] O. Lodge., Mr. Marconis results in day and night wireless telegraphy, Nature, 66, 222,1902.
[6] R.A. Watson-Watt., Weather and Wireless, Q. J.Roy.Metrorol.Soc.,55,273,1929.
[7] B.M. Smirnov, Physics of Ionized Gases; Wiley-VCH Verlag GmbH Co. KGaA, Weinheim, ISBN:0-471-17594-3,2004.
[8] R. Schunk and A. Nagy, Ionospheres: Physics, Plasma Physics, and Chemistry, Cambridge University Press, ISBN;978-0-521-87706-0,2009.
[9] R.P. Singhal, Elements of Space Physics, PHI Learning Private Limited, ISBN:978-81-203-3710-7,2009.
[10] Ed. by M.G. Kivelson and C. T. Russell, Introduction to Space Physics, Cambridge University Press, ISBN:0-521-45104-3,1996.
[11] F W Perkins., space plasma physics: The study of solar-system plasmas, National academy of sciences,1978.
[12] B. Zolesi, L.R. Cander., Ionsopheric Predictions and Forecasting, Springer Geophysics, ISBN 978-3-642-38429-5, DOI 10.1007/978-3-642-38430-1,2014.
[13] N Blaunstein, E. Plohotniuc., Ionosphere and applied aspects of Radio communication and radar, CRC press, Taylor and Francis Group, ISBN 9781138372641,2008.
[14] M. Takashi, Ionosphere and Thermosphere, Journal of the communications research laboratotry,49,3,163-179,2002.
[15] J.G. Luhmann, Ionospheres, Ed. by M.G. Kivelson and C. T. Russell, Introduction to Space Physics, Cambridge University Press,183-202, ISBN:0-521-45104-3,1996.
[16] T.H. Stix, Waves in Plasmas, Springer, ISBN:0-88318-859-7,1992.
[17] W. Horton, Drift waves and transport, reviews of Modern Physics,71,735-778,1999.
[18] M.A. Uman, Introduction to Plasma Physics, McGraw-Hill Book Company, Library of Congress Catalog Card Number 63 21546,1964.
[19] R.A. Treumann and W. Baumjohann, Advanced Space Plasma Physics, Imperial College Press, ISBN: 978-1860940262,2001.
[20] N. A. Krall and A. W. Trivelpiece, Principles of Plasma Physics, McGraw-Hill Book Company, ISBN:978-0070353466,1973.
[21] S.P. Gary, Theory of Space Plasma Microinstabilities, Cambridge University Press, ISBN;0-521-43748-2,2005.

ISSN: 2319-7064
Impact Factor 2025: 7.089

[22] S. Ichimaru, Statistical Plasma Physics, Vol:1, Basic Principles, Taylor and Francis, ISBN 13: 978-0-8133-4178-1,2004.
[23] D.G. Swanson, Plasma Waves, Academic Press, ISBN:978-0124122505,2012.
[24] D.G. Swanson, Plasma Kinetic Theory press, Taylor Francis Group, ISBN 13 978 1 4200 7581 6,2008.
[25] J. Weiland, Stability and Transport in Magnetic Confinement Systems, Springer, ISBN:978-1-4614-3742-0,2012.
[26] P.N. Deka, A Study on Nonlinear Interaction of Waves through Plasma Maser Effect, Ph.D. Thesis, Gauhati University,1997.
[27] K. Ronmark and L. Stenflo, Planetary Space Science,24,904,1976.
[28] M. Nambu and P.K. Shukla, Physical Review A.20,2498,1979.
[29] M. Nambu and P.K. Shukla, Physical Review A.22,787,1980.