Minireview Article

A study on instabilities and nonlinear wave energy exchange process in Terrestrial Ionospheric Plasma

Abstract

From ground and satellite based observatories various forms of nonlinear effects and plasma wave's instabilities are observed in the Earth's ionosphere. To explain these observations nonlinear weak turbulence wave-particle interaction theory is applied for wave energy exchange process between resonant and nonresonant plasma waves. In this paper it has been presented a brief overview on nonlinear wave-particle interaction energy exchange mode *plasma maser instability* and on probable growth rate of high frequency non-resonant waves at different regions of the Earth's ionosphere.

Keywords: Ionospheric plasma, Wave-particle interaction, Plasma maser effect, Growth rate

Introduction

For theoretical and experimental investigations on wave-wave and wave-particle interactions on various observational nonlinear phenomena and instabilities in different regions of Earth's ionosphere, it has been considered ionospheric plasma as a natural laboratory to gain better understanding of the upper atmosphere. Due to low graininess parameter ($g \rightarrow 0$) it has been contemplated ionospheric plasma as collisionless and the collective effects are dominating the whole system [1].

For presence of energy and momentum fluxes from diverse free energy sources in the ionosphere, inhomogeneities are developed due to spatial gradients of physical parameters like density, temperature, pressure etc. The plasma system is perturbed from its equilibrium state in presence of gradients and for the growth of this perturbation, plasma system become unstable and can accumulate energy. To redistributing this accumulated energy, plasma instabilities are the general way leads to transitions of this nonequilibrium thermodynamical state and turbulences [2, 3].

Except Mercury, all planets of our solar system have ionospheric regions. This weakly ionized open plasma ionospheric region acts as interface in between the lower atmosphere and upper atmosphere. Major ingredients of this radio wave reflected region are electrons (< 1eV), ions and few neutral particles. Properties of ionospheres are controlled by diffusions, chemical reactions, turbulences, instabilities and gradients of physical parameters etc [4].

In nonuniform ionospheres plasma, both electrostatic plasma waves like ion sound wave [5, 6], lower hybrid wave [7], Langmuir wave [8, 9, 10, 11], drift wave [7,12] and electromagnetic plasma waves like O-mode [13,14,15] are prevalent. These plasma waves can perturb physical properties in the ionosphere. In the ionospheric plasma region, large scale macro-instabilities and small scale micro-instabilities are observed in different altitudes and regions of the ionosphere. It has been found that ion sound instability, beam driven instability and cyclotron maser instability at auroral ionosphere , lower hybrid instability at E- and F-layers of ionosphere , universal drift instability for all kinds of electrostatic and electromagnetic plasma waves at all conditions in ionosphere , wind-driven instability and Perkins instability at E-regions , Kelvin-Helmholtz instability at F-regions , E X B instability and Auroral electrojet instability at high latitude ionosphere are observed [7,16].

Nonlinear effects and turbulence are observed in nonlinear ionospheric plasma due to energy exchange among collective modes and among plasma particles and plasma waves. According to weak turbulence theory, 3-types of nonlinear interactions are occurring in wave energy exchange process in plasma medium which are wave-wave interaction, wave-particle interaction and wave-particle-wave interaction respectively. In this study it has been concerned only on wave-particle energy exchange process in momentum space.

In 1976 Ronmark and Stenflo [17] had explained generation mechanism of high frequency plasma waves in presence of low frequency waves via waves- particles interaction through the theory of plasma turbulence. In 1983, Nambu [18] had studied on nonlinear interactions of waves and particles and this study had formed the foundation of plasma maser effect. Wave energy up conversion of high frequency waves takes place through this effect which is a high frequency modes and low frequency modes coupling effect. Nambu [18] also proposed that a modulated electric field is developed due to nonlinear coupling between high frequency and low frequency plasma modes and plasma particles are accelerated by this modulated electric field through a nonlinear force. These accelerated resonant particles transfer their energy to the high frequency non resonant modes. From this effect, unstable radiation phenomena are possible in presence of macroscopic inhomogeneity of density gradient, temperature anisotropy, pressure gradients and magnetic field gradients [19] and the efficiency of wave energy up conversion through this effect decreases as difference in wavelengths increases [20]. In Space Physics, plasma maser effect had explained generation mechanism of ULF modulated ELF emissions , Auroral kilometric radiation(AKR),Chorus related electrostatic bursts, Whistler mode in the solar wind and Type III solar radio bursts[21,22,23]. To explain Jupiter's narrow band kilometric radiation , in 1989 Khound et al.[24] had explained this with the help of plasma maser instability and had taken interaction between non-resonant O-mode radiation with resonant ion cyclotron wave. There are other reports on wave energy enhancement of high frequency waves like Berenstein mode [25],ion acoustic wave [26],electromagnetic O-mode [27] in presence of drift wave turbulence in inhomogeneous magnetically confined plasma through plasma maser effect. In 2018, Deka et al.[28] had investigated through this maser effect on amplification of ion acoustic wave in presence of drift wave turbulence in Tokomak plasma.

Different types of radiation emission phenomena and plasma waves instabilities are observed at different altitudes in terrestrial ionospheric plasma from ground and satellite based observatories and are tried to explain these by both linear and nonlinear theories. In nonlinear theoretical model, nonlinear mode-mode couplings are dominant interactions in wave - energy exchange process for plasma waves instabilities. To investigate wave amplifications of plasma waves and its energy enhancement, plasma maser instability is one of the prominent nonlinear wave-particle interaction energy transfer modes in both astrophysical and tokomak plasma environment. In this study it has to find out theoretically probable growth rate of high frequency plasma waves at different regions of the Earth’s ionosphere through plasma maser effect and estimates its approximate value on the basis of observational data.

Analysis

For theoretical investigation on plasma maser instability, governing equations are

$$\left(\frac{\partial}{\partial t}+\vec{v}_j.\frac{\partial}{\partial \vec{r}}-\frac{e_j}{m_j}\left(\vec{E}+\frac{\vec{v}_j\times\vec{B}}{c}\right).\frac{\partial}{\partial \vec{v}_j}\right)f_j\left(\vec{r},\vec{v},t\right)=0 \tag{1}$$

(Vlasov equation)

$$\vec{\nabla}.\vec{E}=-4\pi n_j e_j\int f_j\left(\vec{r},\vec{v},t\right).d\vec{v} \tag{2}$$

(Poisson's equation for electrostatic plasma waves)

$$\vec{\nabla}\times\vec{E}=\frac{1}{c}\frac{\partial\vec{B}}{\partial t} \tag{3}$$

$$\vec{\nabla}\times\vec{B}=\frac{1}{c}\frac{\partial\vec{E}}{\partial t}+\frac{4\pi}{c}\vec{J} \tag{4}$$

(Maxwell's equations for electromagnetic plasma waves)

where f_j is particle distribution function for j^{th} species particles in phase space.

To find fluctuating parts of a distribution function in presence of modulating and modulated fields due to resonant and nonresonant modes and to find dispersion relation & growth rate, usually method of characteristics [29], Fourier transforms, complex residue integration, Bessel's recursion relations, Dirac Delta functions, random phase approximations and causality principles are applied. But the major disadvantage of these complicated and lengthy calculations is that exact solutions are not obtained due to nonlinearity and non-locality of the plasma medium.

Gogoi and Deka [30] had studied on probable amplification of electromagnetic O-mode in presence of low frequency ion sound wave turbulence by plasma maser effect in the ionosphere regime. For this problem it has taken spatial inhomogeneity of density in nonuniform Earth's ionosphere. After lengthy and complex calculations, the approximate expression of growth rate for electromagnetic O-mode has been found as

$$\frac{\gamma_p}{\Omega}=\sqrt{\pi}\left(\frac{\omega_{pj}}{\Omega_j}\right)\left(\frac{e_j}{m_j}\right)^2\frac{1}{v_j^2}\frac{k_{\parallel}^2}{K_{\perp}^2}\frac{1}{\left(\Omega_j-\Omega\right)^2}\exp\left(-\left(\frac{\omega}{k_{\parallel}v_j}\right)^2\right) \tag{5}$$

where ω_{pj} is charged particle plasma frequency, Ω_j is charged particle gyrofrequency , Ω is nonresonat electromagnetic O-mode frequency, $k_{\parallel}$ and $K_{\perp}$ are propagation vectors of low frequency resonant and high frequency nonresonant waves which are parallel and perpendicular directions of magnetic fields respectively. With the help of observational data on the plasma parameters, O-mode plasma wave characteristics in space, ion sound wave parameters and ionospheric parameters from ROSE satellite observations and other sources [31, 32, 33, 34] it has been found approximate growth rate for O-mode as $\frac{\gamma_p}{\Omega} \approx 10^{-5}$. In this investigation it has been found that high frequency O-mode is amplified in presence of ion sound wave in ionospheric plasma due to wave-particle interaction through plasma maser effect.

In another study [35] it is concern on wave energy upconversion of electrostatic nonresonant lower hybrid wave through plasma maser instability in the mid-altitude Earth's ionosphere in where it has been considered gradients in density and magnetic field be present in this thermodynamically nonequilibrium ionospheric plasma state which support drift wave turbulence. The dispersion relation of nonresonant lower hybrid wave in presence of drift wave has been found as

$$\Omega^2 - \omega_{ce}\omega_{ci} = i\frac{F_{Nhz}}{m_j\left(\omega_{ce}^2 - \omega_{ci}^2\right)} \tag{6}$$

where ω_{ce} and ω_{ci} are electron and ion cyclotron frequency respectively and F_{Nhz} is high frequency nonlinear effective force. Approximate growth rate expression of nonresonant lower hybrid wave has been found as

$$\frac{\gamma}{\Omega} = e_j n_{jo}\left(\frac{e_j}{m_j}\right)^2\left(\frac{m_j}{k_B T_j}\right)\frac{K_\parallel(K_\parallel - k_\parallel)}{m_j\left(\omega_{ce}^2 - \omega_{ci}^2\right)}\frac{k_\perp}{k_\parallel^2}\frac{\omega_{pj}^2}{\Omega_j^3\left(\Omega_j - \Omega\right)}E_{l\parallel}^2\frac{\varepsilon'}{\Omega_j}\exp\left\{-\left(\frac{v_d}{v_j}\right)^2\right\} \tag{7}$$

Using observational data of lower hybrid wave, drift wave and plasma parameters in space [36,37, 38,39] and considering density gradient ε'=0.1,the probable growth rate of lower hybrid wave as

$$\frac{\gamma}{\Omega} = 10^{-5}.$$

In another problem [40] it has been studied on probable amplification of electrostatic Langmuir wave in presence of lower hybrid waves turbulence in polar ionospheric plasma, neglecting gradients parameters. Observation of radiation emission phenomena responsible for nonlinear stimulating processes in this zone can lead to interesting theoretical investigations on different aspects. The approximate growth rate expression for Langmuir wave due to plasma maser effect has been found as

$$\frac{\gamma}{\Omega} = \frac{\sqrt{\pi}}{2}E_{l\parallel}\frac{E_{l\parallel}}{4\pi n_j T_j}\left(\frac{e_j}{m_j}\right)^2\frac{\omega_{pj}^4}{\Omega^2\left(\Omega^2 - \Omega_j^2\right)}\frac{k_e^2 K_\parallel}{k_\parallel^2(K_\parallel - k_\parallel)}\left(\frac{v_{lh}}{v_e}\right)\exp\left\{-\left(\frac{v_{lh}}{v_e}\right)^2\right\}. \tag{8}$$

The term $\frac{E_{l\parallel}}{4\pi n_j T_j}\frac{k_e^2}{k_\parallel^2}$ represents low frequency turbulence wave energy and it indicates possibility of wave energy enhancement of Langmuir wave at the expense of low frequency lower hybrid wave turbulence energy. Using observational data from Freja satellite observations at topside polar ionospheric regions and from other sources at the Earth's near space region [41,42, 43] the probable growth rate has been found as 10^{-2} which indicates wave energy enhancement of Langmuir wave .

Discussion

In brief the major findings in this study has been found as plasma maser effect has demonstrated a decisive role in amplification or wave energy up conversion of nonresonant electromagnetic and electrostatic waves in presence of resonant waves in ionospheric plasma. The density gradient may play the role of free source of energy and momenta in plasma wave amplification process. The wave energy up conversion process is driven by a high frequency nonlinear force. Low frequency plasma waves transfer its energy through nonlinear wave-particle interaction for enhancement of nonresonant modes in an open system. Future possible extension works based on these studies are plasma maser effect may be one of the sources for secondary electromagnetic radiation phenomenon in top ionospheric and magnetospheric region and in enhancing the instability of plasma waves, it should include the temperature gradient and pressure gradient in the particle distribution function.

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