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# Conversion of Ion-acoustic Waves into Electromagnetic Waves in Presence of Density Gradient in Ionosphere and Solar Corona

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**Abstract.** Theoretical investigations have been made regarding the conversion of longitudinal ion-acoustic waves into transverse electromagnetic radiation due to coupling phenomenon in inhomogeneous plasmas. Coupling equations of ion-acoustic and electromagnetic waves, expressions for the Poynting flux of the radiating electromagnetic waves and the mode conversion ratio have been derived. Numerical estimations of the mode conversion efficiency and the radiating Poynting flux have been made for typical F region ionospheric and solar coronal plasmas. The importance of the result is also discussed.

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## 1 Introduction

Radiation of electromagnetic waves from ionosphere, solar corona and hot astrophysical bodies has been one of the most important and interesting phenomena for study. Different authors have suggested different mechanisms for such radiations. Mode conversion of longitudinal plasma waves into electromagnetic waves has been accepted as one such mechanism. In uniform infinite plasma perturbations travel as longitudinal and transverse waves but in this idealization no coupling between these two modes and hence no transfer of power from one mode to the other is possible. But a wave launched into nonuniform plasma can in a short distance completely change its character to another type of wave by a process known as mode conversion. In a slowly varying medium with the wavelength of propagation much smaller than the characteristic length of variation of equilibrium density, the pressure and the transverse perturbation fields are mutually connected and so there results in mutual coupling between longitudinal and transverse waves. Field [1] showed that the longitudinal plasma waves and transverse electromagnetic waves are coupled in a plasma in presence of density gradient and static magnetic field and by this process radiation of electromagnetic waves is possible in astrophysical bodies. Consideration of inhomogeneous plasma is justified because most astrophysical hot bodies are surrounded by sheet of ionized gas which is generally nonuniform. He applied the model in solar flare ejection. In fact this idea of coupling between longitudinal plasma waves and transverse electromagnetic waves in inhomogeneous plasma medium can explain some important results in the context of astrophysical phenomena [2]. For example, the radio noise in the ionosphere may be one of the consequences of the energy conversion of electro-acoustic waves. Tidman [3] investigated the coupling of waves in a plasma considering the gradients of electron density and temperature. He obtained expressions for radio noise excited by plasma oscillations for two extreme cases: (a) gradients with a length scale much greater than the wavelength of the plasma wave, (b) the presence of density discontinuities. Very recently direct space craft observation of wave mode conversion between the Alfven and slow mode waves in the magnetotail due to sharp curvature of the background magnetic field has been reported [4]. In fact the problem of mode conversion is potentially relevant to various process including solar radio emissions, ionospheric radar experiments, laboratory plasma devices and pulsars. For this the problem of the coupling of waves and mode conversion in inhomogeneous plasma has been the subject of numerous investigations [5-21]. The 'Introduction' section of Ref. [17] provides a good thorough review of the literature developed since mode conversion was first proposed theoretically [1]. The results of plasma wave coupling theories have been applied to solar bursts and ionospheric F region [9,10]. Chakraborty [11] considered the coupling mechanism as an interaction due to a slowly varying density under WKB approximation. He considered the case of warm compressible two fluid plasmas and obtained coupling equations for longitudinal electro-acoustic and transverse electromagnetic waves. Chakraborty [11] investigated the energy conversion problem under far field approximation. Later Khan and Paul [10] used WKB approximation by considering the slowly varying equilibrium density and showed that the incident electro-acoustic waves interacting with slowly varying density generate reflected and transmitted electromagnetic waves and energy is transferred from compressional type of waves to electromagnetic waves. They calculated the Poynting flux of the reflected and transmitted electromagnetic radiation and the energy flux of the incident wave in ionospheric plasma. In the limit of most randomly fluctuating density the coupling between the longitudinal and transverse modes has to be considered from an entirely different point of view [13]. The inverse process, *i.e.*, the conversion of electromagnetic waves into longitudinal plasma waves is also possible. Paul [14] and Paul *et al*. [15] have considered the conversion of electromagnetic waves into longitudinal waves in hot inhomogeneous plasma under far field approximation.

According to Paul [14] this energy conversion plays an important role in the expansion of ionized shell of hot stars and consequent ejection of matter from it. In fact he has applied the results to estimate the amount of mass ejection from the surface of a few hot astrophysical bodies such as Be stars, OB-supergiant and Wolf-Rayet star.

Thus so far different authors have considered the radiation mechanisms of electromagnetic waves due to coupling phenomenon by electro-acoustic waves in inhomogeneous plasmas but none of the previous authors considered the ion-acoustic waves with due attention for the study of the radiating electromagnetic waves from astrophysical objects. Motivation of the present paper is to investigate the possibilities of the radiation of electromagnetic waves by the conversion of ion-acoustic waves in the ionosphere and solar corona, assuming the plasma to be warm and inhomogeneous.

The paper is organized in the following way. In Section 2 we derive the coupling equations for ion-acoustic and electromagnetic waves from linearized plasma equations. We obtain the expression for the energy flux of the incident wave in Section 3, the expression for the Poynting flux of the radiating electromagnetic waves in Section 4 and the mode conversion ratio in Section 5. Numerical estimations for the mode conversion efficiency and the Poynting flux of the radiating electromagnetic waves from the ionosphere and solar corona are given in Section 6. The paper ends up with some concluding remarks in Section 7.

## 2 Formulations

It is well-known that the plasmas of the ionosphere and the solar corona are generally inhomogeneous. For theoretical study we therefore assume such plasmas to be inhomogeneous. However we neglect the presence of any static magnetic field and collision effect between ions and electrons. Therefore, the basic equations for non-relativistic plasma dynamics are the following:

The equations of motion:

$$\frac{\partial \boldsymbol{u}_j}{\partial t} = -\frac{1}{m_j N_0}\nabla p_j + \frac{q_i}{m_j}\boldsymbol{E}. \tag{1}$$

The equations of continuity:

$$\frac{\partial N_j}{\partial t} + N_0(\nabla \cdot \boldsymbol{u}_j) + (\nabla N_0)\cdot \boldsymbol{u}_j = 0. \tag{2}$$

Maxwell's equations (in Gaussian units):

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{H}}{\partial t}, \tag{3}$$

$$\nabla \times \boldsymbol{H} = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} + \frac{4\pi e N_0}{c}(\boldsymbol{u}_i - \boldsymbol{u}_e), \tag{4}$$

$$\nabla \cdot \boldsymbol{E} = 4\pi e(N_i - N_e) \tag{5}$$

and

$$\nabla \cdot \boldsymbol{H} = 0. \tag{6}$$

The equation of state is:

$$p_j = m_j c_j^2 N_j, \tag{7}$$

where $j = e$ for electrons and $i$ for ions, $q_e = -e$, $q_i = e$; $\boldsymbol{u}_j$ is the fluid velocity, $m_j$ is the mass, $N_j$ is the number density $c_j = \sqrt{k_B T_j/m_j}$ is the thermal speed and $p_j$ is the pressure of the $j$-th species; $N_0$ is the equilibrium density and other parameters have their usual significance. The equilibrium parameters are assumed to be slowly varying functions of position.

Assuming the time dependence of the field parameters to be $\sim \exp(-i\omega t)$, $\omega$ being the wave frequency, we obtain from Eqs. (1)–(7) the following linearized coupling equations between purely transverse magnetic field variables and the longitudinal pressure perturbations:

$$\Big[\nabla^2 + \frac{\omega^2 - \omega_{pe}^2}{c^2}\Big]\boldsymbol{H}_1 = -\frac{1}{\mu}[\nabla\mu \times (\nabla \times \boldsymbol{H}_1)] + \frac{i}{\mu}[\nabla\mu_e \times \nabla p_e] - \frac{i}{\mu}[\nabla\mu_i \times \nabla p_i], \tag{8}$$

$$\Big[\nabla^2 + \frac{\omega^2 - \omega_{pi}^2}{c_i^2}\Big]p_i + \frac{\omega_{pe}^2}{c_e^2}p_e = -\frac{i}{\mu}[\nabla\mu \cdot (\nabla \times \boldsymbol{H}_1)] - \frac{1}{\mu}[\nabla\mu_e \cdot \nabla p_e] + \frac{1}{\mu}[\nabla\mu_i \cdot \nabla p_i], \tag{9}$$

$$\Big[\nabla^2 + \frac{\omega^2 - \omega_{pe}^2}{c_e^2}\Big]p_e + \frac{\omega_{pi}^2}{c_i^2}p_i = \frac{i}{\mu}[\nabla\mu \cdot (\nabla \times \boldsymbol{H}_1)] + \frac{1}{\mu}[\nabla\mu_e \cdot \nabla p_e] - \frac{1}{\mu}[\nabla\mu_i \cdot \nabla p_i], \tag{10}$$

where

$$\mu_j = 1 - \frac{\omega_{pj}^2}{\omega^2}, \quad \boldsymbol{H}_1 = \frac{\omega c M}{4\pi e}\boldsymbol{H}, \quad \omega_{pj}^2 = \frac{4\pi N_0 e^2}{m_j},$$
$$M = \frac{m_e m_i}{m_e + m_i}, \quad \mu = (\mu_e + \mu_i) - 1.$$

It is to be noted that the wave equation for the magnetic field vector contains source terms depending on the pressure perturbations and the wave equation for the pressure perturbation contains source terms depending on the magnetic field vector. These source terms vanish for uniform equilibrium concentration. We assume that the gradient of density is along $z$-direction and the disturbance propagates in the $(x, z)$ plane. Therefore, eliminating $p_e$ from Eqs. (9) and (10), we may obtain

$$\Box p_i = \frac{c_i^2}{\mu}[c_e^2\nabla^2 + \omega^2]\{-i[\nabla\mu\cdot(\nabla\times\boldsymbol{H}_1)] - (\nabla\mu_e\cdot\nabla p_e) + (\nabla\mu_i\cdot\nabla p_i)\}, \quad (11)$$

where

$$\Box = (c_e^2\nabla^2 + \omega^2 - \omega_{pe}^2)(c_i^2\nabla^2 + \omega^2 - \omega_{pi}^2) - \omega_{pe}^2\omega_{pi}^2. \quad (12)$$

Since $c_i^2\omega_{pe}^2 = c_e^2\omega_{pi}^2$, Eq. (12) can be written in the form,

$$\Box = k^4c_e^2c_i^2 - k^2[(c_e^2+c_i^2)\omega^2 - c_e^2\omega_{pi}^2(1+T_i/T_e)] + \omega^4 - \omega^2(\omega_{pe}^2 + \omega_{pi}^2). \quad (13)$$

Moreover, since

$$c_i^2 \ll c_e^2, \quad \omega_{pi}^2 \ll \omega_{pe}^2, \quad T_i \ll T_e$$

and $\omega^2 \ll \omega_{pi}^2(1 + T_i/T_e)$ for ion-acoustic wave, (13) reduces to

$$\Box \approx k^4c_e^2c_i^2 + k^2c_e^2\omega_{pi}^2 - \omega^2\omega_{pe}^2.$$

Or,

$$\frac{m_e}{m_i}\Box = k^4c_s^2c_i^2 + k^2c_s^2\omega_{pi}^2 - k^2c_i^2\omega^2 - \omega^2\omega_{pi}^2.$$

Since $c_i^2\omega^2$ is small, we can write,

$$\frac{m_e}{m_i}\Box = (k^2c_s^2 - \omega^2)(k^2c_i^2 + \omega_{pi}^2), \quad (14)$$

where $c_s^2 = k_BT_e/m_i$, $c_s$ is the ion-acoustic speed and $k_B$ is the Boltzmann constant.

So using (14), the coupling equation (11) becomes

$$\Big(c_s^2\nabla^2 - \frac{\partial^2}{\partial t^2}\Big)(c_i^2\nabla^2 - \omega_{pi}^2)p_i = \frac{m_e}{m_i}\,\frac{c_i^2}{\mu}\Big[c_e^2\nabla^2 - \frac{\partial^2}{\partial t^2}\Big] \times \{-i[\nabla\mu\cdot(\nabla\times\boldsymbol{H}_1)] - [\nabla\mu_e\cdot\nabla p_e] + [\nabla\mu_i\cdot\nabla p_i]\}. \quad (15)$$

Let us consider the ion-acoustic pressure perturbations as the only source of excitation of a wave and the coupling to be caused only by the inhomogeneity of the plasma. Other sources of coupling between ion-acoustic wave and electromagnetic wave are not taken into account. Therefore, Eq. (15) yields

$$\Big(c_s^2\nabla^2 - \frac{\partial^2}{\partial t^2}\Big)(c_i^2\nabla^2 - \omega_{pi}^2)p_i = 0. \quad (16)$$

The term $(c_i^2\nabla^2 - \omega_{pi}^2)$ gives a non-propagating wave and we neglect it. So, Eq. (16) becomes

$$\Big(c_s^2\nabla^2 - \frac{\partial^2}{\partial t^2}\Big)p_i = 0. \tag{17}$$

Now we assume the $x$-dependence of the ion-acoustic wave to be of the form $\exp(ik_0x)$, $k_0$ being a constant. Thus, we can write

$$p_i = p_i(z)e^{ik_0x}. \tag{18}$$

Therefore, Eq. (17) becomes

$$\frac{\partial^2 p_i(z)}{\partial z^2} + k_1^2 n_i(z) = 0, \tag{19}$$

where

$$k_1^2 = \frac{\omega^2 - k_0^2c_s^2}{c_s^2}\,. \tag{20}$$

Therefore, for a forward going wave the solution of (17) may be written as

$$p_i = p_0\exp\{i(k_1z + k_0x - \omega t)\}. \tag{21}$$

To find the radiating electromagnetic wave due to conversion of ion-acoustic wave, we first neglect the slowly varying term on the right hand side of equation (8), then using the value of

$$p_e = \Big(\frac{c_e^2}{\omega_{pe}^2}\Big)\Big(\nabla^2 + \frac{\omega^2 - \omega_{pi}^2}{c_i^2}\Big)p_i,$$

obtained from (9) and (10), we get

$$\Big(\nabla^2 + \frac{\omega^2 - \omega_{pe}^2}{c_i^2}\Big)\boldsymbol{H}_1 = \frac{i}{\mu}e_y\Big[\frac{c_e^2}{\omega_{pe}^2}\Big(\frac{\partial\mu_e}{\partial z}\Big) \times\Big\{k_2^2\frac{\partial p_i}{\partial x} - \frac{\partial}{\partial x}\Big(-\frac{\partial^2 p_i}{\partial z^2}\Big)\Big\} - \Big(\frac{\partial\mu_i}{\partial z}\Big)\Big(\frac{\partial p_i}{\partial x}\Big)\Big]. \tag{22}$$

Since $\partial\mu_i/\partial z$ is small in comparison to $\partial\mu_e/\partial z$, we neglect $\Big(\frac{\partial\mu_i}{\partial z}\Big)\Big(\frac{\partial p_i}{\partial x}\Big)$ and the higher order derivatives. So Eq. (22) reduces to

$$\Big(\nabla^2 + \frac{\omega^2 - \omega_{pe}^2}{c_i^2}\Big)\boldsymbol{H}_1 = \frac{i}{\mu}e_y\frac{c_e^2}{\omega_{pe}^2}\Big(\frac{\partial\mu_e}{\partial z}\Big)k_2^2\frac{\partial p_i}{\partial x}\,, \tag{23}$$

where

$$k_2^2 = k_0^2 - \frac{\omega^2 - \omega_{pi}^2}{c_i^2}\,. \tag{24}$$

The solution of (23) is

$$\boldsymbol{H}_1 = \frac{1}{\mu} e_y \Big[ \frac{c_e^2 c_s^2 k_2^2 k_0 p_0}{\omega^2 \omega_{pe}^2} \Big( \frac{\partial \mu_e}{\partial z} \Big) \exp\{i(k_1 z + k_0 x - \omega t)\} \Big]. \qquad (25)$$

Therefore,

$$\boldsymbol{H} = \frac{4\pi e \boldsymbol{H}_1}{\omega c M} = -e_y \Big[ \frac{4\pi e c_e^2 c_s^2 k_2^2 k_0 p_0}{\mu \omega^3 \omega_{pe}^2 c M} \Big( \frac{\omega_{pe}^2}{\omega^2 L} \Big) \exp\{i(k_1 z + k_0 x - \omega t)\} \Big], \quad (26)$$

where $L$ is the characteristic length of the density variation. Since the $(x, z)$ plane is the plane of incidence, the transverse field vector $\boldsymbol{H}$ is in the $y$-direction. Therefore,

$$H_y = -\Big[ \frac{4\pi e c_e^2 c_s^2 k_2^2 k_0 p_0}{\mu \omega^5 c M_1 L} \exp\{i(k_1 z + k_0 x - \omega t)\} \Big]. \qquad (27)$$

## 3 Energy Flux of the Incident Wave

The energy flux density of the incident longitudinal pressure wave is the product of real values of the pressure perturbation and the velocity perturbation. The $z$-component of which is

$$\begin{aligned} \omega_{pe} = 4 \times 10^7 S_{1z} &= (u_{iz} p_i) \\ &= \mathrm{Re}\Big[ \frac{-i}{m_i(\omega^2 - \omega_{pi}^2)} \Big\{ \frac{\omega}{N_0} \frac{\partial p_i}{\partial z} + c_e k_0 H_y \Big\} \Big] \cdot \mathrm{Re}(p_i). \qquad (28) \end{aligned}$$

Substituting the real values and averaging over time period $2\pi/\omega$, the incident energy flux becomes

$$|\langle S_{1z} \rangle| = \Big| \frac{\omega k_1 p_0^2}{2 N_0 m_i (\omega^2 - \omega_{pi}^2)} \Big|. \qquad (29)$$

## 4 Poynting Flux of the Radiating Electromagnetic Wave

To estimate the Poynting energy flux of the propagating waves through a slowly varying plasma, we neglect collisional dissipation. The electric field of the radiating electromagnetic wave becomes

$$E = \frac{i\omega c [\nabla \times \boldsymbol{H}]}{(\omega^2 - \omega_{pi}^2)} - \frac{4\pi e \nabla p_i}{m_i (\omega^2 - \omega_{pi}^2)}. \qquad (30)$$

The $x$- and $z$-components of $\boldsymbol{E}$ are

$$E_x = -\frac{i\omega c}{(\omega^2 - \omega_{pi}^2)} \frac{\partial H_y}{\partial z} - \frac{4\pi e i k_0 p_i}{m_i(\omega^2 - \omega_{pi}^2)} \qquad (31)$$

and

$$E_z = \frac{i\omega c}{(\omega^2 - \omega_{pi}^2)} \frac{\partial H_y}{\partial x} - \frac{4\pi e}{m_i(\omega^2 - \omega_{pi}^2)} \Big(\frac{\partial p_i}{\partial z}\Big). \tag{32}$$

Using (27), we get

$$E_x = -\frac{4\pi e c_e^2 c_s^2 k_0 k_1 k_2^2 p_0}{\mu\omega^4 m_i(\omega^2 - \omega_{pi}^2)} \exp\{i(k_1 z + k_0 x - \omega t)\} - \frac{4\pi e i k_0 p_e}{m_i(\omega^2 - \omega_{pi}^2)} \exp\{i(k_1 z + k_0 x + \omega t)\} \tag{33}$$

and

$$E_z = \frac{4\pi e c_e^2 c_s^2 k_0^2 k_2^2 p_0}{\mu\omega^4 M(\omega^2 - \omega_{pi}^2) L} \exp\{i(k_1 z + k_0 x - \omega t)\} - \frac{4\pi e i k_1 p_0}{m_i(\omega^2 - \omega_{pi}^2)} \exp\{i(k_1 z + k_0 x - \omega t)\}. \tag{34}$$

The Poynting flux of the radiated electromagnetic field is given by

$$\boldsymbol{S}_t = \frac{c}{4\pi}[\boldsymbol{E} \times \boldsymbol{H}]. \tag{35}$$

The $z$-component of $\boldsymbol{S}_t$ is

$$S_{tz} = \frac{c}{4\pi}(\mathrm{Re}\, E_x \cdot \mathrm{Re}\, H_y). \tag{36}$$

Now substituting the real values of $E_x$ and $E_y$ from (33) and (29) and averaging over time period $2\pi/\omega$, the $z$-component of Poynting flux becomes

$$\langle S_{tz} \rangle = \Big| \frac{\omega_{pi}^2 c_e^4 c_s^4 k_0^2 k_1 k_2^4 p_{{}_0}^2}{2N_0 m_i \mu^2 \omega^9 (\omega^2 - \omega_{pi}^2) L^2} \Big|. \tag{37}$$

## 5 Mode Conversion Ratio

The quantity of practical importance is the fraction of the energy of the incident longitudinal wave that is converted into electromagnetic radiations. So we calculate the mode conversion ratio ($\beta$) given by the ratio of the electromagnetic energy flux and the incident energy flux. Thus, from Eqs. (29) and (37), we get

$$\beta = \frac{\omega_{pi}^2 c_e^4 c_s^4 k_o^2 (\omega^2 - \omega_{pi}^2 - k_o^2 c_i^2)^2}{c_i^4 \omega^6 L^2 (\omega^2 - \omega_{pi}^2 - \omega_{pe}^2)^2}\ . \tag{38}$$

Note that the mode conversion ratio depends on the frequency of the longitudinal wave as well as the scale length of density variation.

## 6 Results and Discussions

The coupling effect between ion-acoustic waves and electromagnetic waves in a slowly varying inhomogeneous plasma produces electromagnetic radiation. The Earth's ionosphere is a natural example of non-uniform medium where the density of electron is a slowly varying function of position. The ion-acoustic wave is supposed to generate electromagnetic radiations when penetrating into the ionospheric F region. Ion-acoustic waves may be produced due to turbulent motion, mass flow into or out of the plasma volume or by an artificially created explosion. Let the frequency of the longitudinal wave be $\omega = 10^5$ rad/s. As the ionospheric F region is at high altitude (about 250–350 km) we take pressure amplitude to be of the order of 10 N/m$^2$. We consider the high temperature model for F region [22] where electron temperature, $T_e = 1700$ K and ion temperature $T_i = 1100$ K; equilibrium electron density $N_0 = 5 \times 10^{11}$ m$^{-3}$. Therefore, the parameters $\omega_{pi} = 2.2 \times 10^5$ rad/s, $\omega_{pe} = 4 \times 10^7$ rad/s; $k_0 = 1.5 \times 10^{-2} k_1 = 1.22$. Remembering the condition for slowly varying medium $(L \gg \lambda)$, we take $L \sim 50$ m for ionospheric F region. In this case the energy flux density of the incident ion-acoustic wave as calculated from Eq. (29) is $19 \times 10^{10}$ W/m$^2$ and the energy flux density of the generated electromagnetic radiation as calculated from Eq. (37) is $1.56 \times 10^{10}$ W/m$^2$. Hence, the conversion efficiency in this case is about 8%. Though the conversion efficiency appears to be small, the process may become extremely efficient when the wave frequency approaches the plasma frequency in the region of inhomogeneity or the scale length of density variation becomes small.

It is obvious from Eq. (37) that the power of the generated electromagnetic radiations varies inversely as the square of the characteristic length ($L^2$) of the density variation. Using the above data for the F region of the ionosphere we find that the radiating Poynting flux varies in the range $6.24 \times 10^{10}$ W/m$^2$ to $3.90 \times 10^9$ W/m$^2$ for $L$ in the range 25 m to 100 m. Obviously there is a sharp decrease in the electromagnetic radiation with the increase in the scale length of density variation. Here we must point out that the coupling between the longitudinal and transverse waves due to density gradient becomes important when the inhomogeneity is a slowly varying function of position and the characteristic length of variation is greater than the wavelength of the transmitted wave $(L \gg \lambda)$.

Another possible area of application of the analysis presented in the present paper is the narrow transition layer between the solar chromospheres and the corona, where there is a large gradient of density and temperature. During the period of solar activities, *e.g.*, solar bursts, different types of waves including electromagnetic waves are emitted. Observational results indicate that electromagnetic energy is emitted during type II and III solar bursts and ionized gases come out from the surface of the sun with velocity in the range 1000–2000 km/s. One of the possible mechanisms for electromagnetic radiation is the conversion of longitudinal waves into electromagnetic waves due to coupling of the waves through the inhomogeneity. From expression (37) we have estimated Poynting flux of the converted electromagnetic wave in the solar corona for different scale lengths of density variation, taking the amplitude of the ion-acoustic pressure wave $\sim 10^2$ N/m$^2$, the equilibrium electron number density $(N_0) \approx 1.6 \times 10^{14}$ m$^{-3}$, ion-acoustic wave frequency $\omega = 10^6$ rad/s and the temperature of the plasma as $10^6$ K. It is found that the radiating Poynting flux varies in the range $2.08 \times 10^7$ W/m$^2$ to $8.32 \times 10^5$ W/m$^2$ for $L$ in the range 100 m to 500 m.

Modern satellite-based diagnostic methods can be used to study the conversion mechanism of longitudinal plasma waves into electromagnetic waves in the ionosphere. This will in turn help to understand the main conversion mechanism taking place in the coronas of the Sun and other stars. Mode conversion mechanism can be a great benefit for the use of waves to heat and control fusion plasmas. It is also potentially relevant to various process including solar radio emissions, ionospheric radar experiments, laboratory plasma devices and pulsars.

## 7 Some Concluding Remarks

We have investigated the coupling of longitudinal and transverse waves in inhomogeneous plasma of the ionosphere and solar corona which leads to the conversion of ion-acoustic waves into electromagnetic radiation. It is observed that electromagnetic radiations both from the ionosphere and the solar corona are significant and this may help to understand some physical processes going on in the ionosphere and the solar corona. However we must point out here that a quantitative comparison of the theoretical Poynting flux with the observation during solar bursts may show some discrepancies, because in our present analysis we have considered only the conversion of the ion-acoustic mode. Moreover, we have not considered the presence of magnetic field and temperature gradients which can also act as a coupling agent. Inclusion of relativistic effects is also important particularly during the period of solar activities. So in order to get a more complete picture of the conversion of ion-acoustic waves into electromagnetic radiation one may extend the present analysis by incorporating nonlinear effects as well as the effects of magnetic field, temperature gradient and relativistic stream velocities of the electrons and ions. The parametric interaction between longitudinal and transverse waves in inhomogeneous plasma may also play a definite role in the understanding of the electromagnetic radiations from astrophysical objects. In order to have a complete picture of electromagnetic radiation it is essential to incorporate in the analysis all the above effects. At present we are trying to incorporate a few such effects into our analysis.

Finally we would like to point out that the inverse process, *i.e.*, the conversion of electromagnetic waves into ion-acoustic waves is also possible in a non-uniform plasma. Analysis of this mechanism is important because it may play an important role in the ejection of matter from hot astrophysical bodies.

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