NONLINEAR ELECTROMAGNETIC WAVE PROPAGATION IN A MAGNETOACTIVE FINITE TEMPERATURE PLASMA

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ABSTRACT

A system of ordinary nonlinear differential equations, governing the scalar and vector potentials associated with a one-dimensional electromagnetic wave in a hot plasma, has been derived using a properly constructed stationary solution of the nonlinear Boltzmann-Vlasov equation in a moving reference frame. The propagation of the transverse electromagnetic wave is considered for three cases: no applied static electromagnetic field, a static magnetic field in the direction of wave propagation, and static electric and magnetic fields in the direction of propagation.

In the static field-free case, assuming electrical neutrality and considering an electron temperature anisotropy in the plasma, the derived dispersion relation indicates that the wavelength of the transverse electromagnetic wave is amplitude dependent. In the second case, the transverse electromagnetic wave appears as a circularly polarized sinusoidal wave in a laboratory frame of reference. For an electrically neutral plasma with a small-temperature anisotropy and whose mean velocity in the direction of wave propagation vanishes, the derived dispersion relation reduces to the commonly quoted dispersion relation for Alfven waves.

The influence of a static electric field along the direction of propagation is studied and it is found that under small-amplitude and weak static electric field conditions, the transverse electromagnetic wave appears as an elliptically polarized plane wave in the laboratory frame. The effect of the static electric field on the wavelength and the Faraday rotation is investigated and discussed.
TABLE OF CONTENTS

ABSTRACT  iii

LIST OF ILLUSTRATIONS  v

I. INTRODUCTION  1

II. BASIC EQUATIONS  2

III. PLASMA IN COMBINED ELECTROSTATIC AND MAGNETOSTATIC FIELDS  13

IV. BEHAVIOR OF TRANSVERSE ELECTROMAGNETIC FIELDS  20

V. DISCUSSION OF RESULTS  39

APPENDIX A. DERIVATION OF EQS. 42 AND 43  43

LIST OF REFERENCES  49


# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plot of ( Y ) vs. ( X ) for ( \sigma = 0.01, s = 0.1, ) and ( Y_o = 0.1, 0.5, 1.0. )</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>Plot of ( Y ) vs. ( X ) for ( \sigma = 0.4, s = 0.4, ) and ( Y_o = 0.5, 1.0. )</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Plot of ( Y ) vs. ( X ) for ( \sigma = 0.01, Y_o = 1.0, ) and ( S = 0.1, -0.1. )</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>Plot of ( Y ) vs. ( X ) for ( \sigma = 0.01, Y_o = 1.0, ) and ( s = 0, \pm 0.001, \pm 0.01. )</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>Plot of ( Y ) vs. ( X ) for ( s = 0.1 ) and ( Y_o = 1.0, ) with ( \sigma ) as a parameter.</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>Plot of ( Y ) vs. ( X ) for ( s = 1.0, Y_o = 1.0, ) and ( \sigma = 0.01, 0.4, 1.0. )</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>Plot of ( Y ) vs. ( X ) based on Eq. 60a for ( s \neq 0 ) and ( 3\sigma^2 \ll 1. )</td>
<td>34</td>
</tr>
</tbody>
</table>
NONLINEAR ELECTROMAGNETIC WAVE PROPAGATION IN A MAGNETOACTIVE FINITE TEMPERATURE PLASMA

I. INTRODUCTION

The study of electromagnetic wave propagation in a plasma has application in many diverse fields of physics such as, for example, the interpretation of microwave diagnostic data obtained from laboratory plasmas\(^1,2,3\), astrophysical problems such as the generation of cosmic r-f radiation\(^4\), and the entire field of radio wave propagation in the ionosphere\(^5,6\). This wide range of interests in the basic problem has led in recent years to many theoretical studies of plasma oscillations\(^7-13\).

The only dynamical plasma phenomena that have been treated in a satisfactory way are those describable in terms of small-amplitude departures from uniform equilibria. Many, if not most, plasmas—both laboratory and astrophysical—do not fit such a description. The number of nonlinear problems which have been solved to date is rather limited. In particular, two kinds of nonlinear plasma configurations have been investigated. In the first, which is known as a "constant profile" description, there exists a "wave" coordinate system in which all quantities appear to be time-independent. A "laboratory" observer, in general, would not view the phenomena from this particular frame, but all macroscopic variables would appear to have the form of \((\vec{r} - \vec{v}_0 t)\), where the velocity \(\vec{v}_0\) is a constant, and \(\vec{r}\) and \(t\) are the position and time variables respectively. The more usual approach is to study the problem in a coordinate frame which moves with the velocity \(\vec{v}_0\) and refer the result back to laboratory coordinates at the end. The more
general nonlinear problems involve situations in which no such preferred frame exists; a simple example would be the steepening of nonlinear sound waves according to the Euler equation\textsuperscript{14}.

The former approach has been used to study magnetosonic waves in a cold plasma\textsuperscript{15} as well as the nonlinear Alfv\textendash en waves\textsuperscript{16,17,18}. Nekrasov\textsuperscript{19} has studied the steady-state nonlinear motion of an electron-ion plasma by a similar approach. In the present paper an attempt is made to study the interaction of plasma with a propagating electromagnetic plane wave in a wave frame, using the one-dimensional Boltzmann-Vlasov equation and Maxwell's equations.

II. BASIC EQUATIONS

Consider a two-component plasma (positive ions and electrons) in which the effects of collisions are assumed to be negligible. The electron distribution function $f(r,v,t)$ and the ion distribution function $F(r,v,t)$ for this plasma are governed by the Boltzmann-Vlasov equations written as follows:

\[
\frac{\partial f}{\partial t} + \vec{v} \cdot \nabla f - \frac{e}{m} (\vec{E} + \vec{v} \times \vec{B}) \cdot \nabla_v f = 0 \tag{1a}
\]

and

\[
\frac{\partial F}{\partial t} + \vec{v} \cdot \nabla F + \frac{e}{M} (\vec{E} + \vec{v} \times \vec{B}) \cdot \nabla_v f = 0 \tag{1b}
\]

where $m$ and $M$ denote, respectively, the mass of the electron and ion, and $e$ is the electronic charge which is taken as a positive quantity.

The electromagnetic fields in the plasma are governed by the Maxwell equations:
The electric displacement vector $\mathbf{D}$ and the magnetic flux density $\mathbf{B}$ are, respectively, related to the electric field intensity $\mathbf{E}$ and the magnetic field intensity $\mathbf{H}$ in the usual manner:

$$\mathbf{D} = \varepsilon_0 \mathbf{E}$$  \hspace{1cm} (3a)$$

and

$$\mathbf{B} = \mu_0 \mathbf{H}$$  \hspace{1cm} (3b)$$

where $\varepsilon_0$ and $\mu_0$ denote the dielectric constant and the permeability of vacuum respectively. The convection current density $\mathbf{J}$ and the charge density $\rho$ may be given in terms of the distribution functions as

$$\mathbf{J} = e \int (\mathbf{v}(\mathbf{P} - \mathbf{r})) d^3v$$  \hspace{1cm} (4a)$$

and

$$\rho = e \int (\mathbf{P} - \mathbf{r}) d^3v$$  \hspace{1cm} (4b)$$

It is well known that the analysis of electromagnetic fields is often facilitated by the use of auxiliary potential functions. A general solution of the inhomogeneous system (Eqs. 2) can be given as follows:

$$\mathbf{E} = -\nabla \Phi - \frac{\partial \mathbf{A}}{\partial t} - \frac{1}{\varepsilon_0} \nabla \times \mathbf{A}_0$$  \hspace{1cm} (5a)$$

and

$$\mathbf{B} = \nabla \times \mathbf{A} - \mu_0 \frac{\partial \mathbf{A}_0}{\partial t} - \mu_0 \nabla \Phi_0$$  \hspace{1cm} (5b)$$

where $\Phi$ and $\mathbf{A}$ are the potentials of the source distribution which is internal to the region under consideration, and $\Phi_0$ and $\mathbf{A}_0$ are potentials...
of the source distribution which is entirely external to the region under consideration. These potentials are subject to the following conditions:

\[ \Box \vec{A} = -\mu_0 \vec{J} , \]  
\[ \Box \phi = -\frac{1}{\varepsilon_0} \rho , \]  
\[ \nabla \cdot \vec{A} + \mu_0 \varepsilon_0 \frac{\partial \phi}{\partial t} = 0 , \]  
\[ \Box \vec{A}_o = 0 , \]  
\[ \Box \phi_0 = 0 \]  
and
\[ \nabla \cdot \vec{A}_o + \mu_0 \varepsilon_0 \frac{\partial \phi_0}{\partial t} = 0 , \]

where the symbol \( \Box \) denotes the D'Alembertian operator defined by

\[ \Box \equiv \nabla^2 - \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} . \]

Define an equivalent potential function \( \vec{a} \) by the following differential equations:

\[ \frac{\partial \vec{a}}{\partial t} = \frac{1}{\varepsilon_0} \nabla \times \vec{A}_o \]  
and
\[ \nabla \times \vec{a} = -\mu_0 \left( \frac{\partial \vec{A}_o}{\partial t} + \nabla \phi_0 \right) , \]

so that Eqs. 5 can be written as

\[ \vec{E} = -\nabla \phi - \frac{\partial \vec{V}}{\partial t} \]  
and
\[ \vec{B} = \nabla \times \vec{V} , \]

where
\[ \vec{V} = \vec{A} + \vec{a} . \]
It should be noted that the set of Eqs. 8, which is equivalent to the set of Eqs. 7a-c, can also be written as

\[ \Box \vec{a} = 0 \quad \text{and} \quad \nabla \cdot \vec{a} = 0 \quad . \quad (10) \]

Postulate the existence of a moving frame of reference in which all quantities of interest appear to be stationary, i.e., a transformation \( \xi = (z - v_0 t) \) is made to a moving coordinate system where \( v_0 \) is a constant independent of \( t \) and \( z \), and thus \( \xi \) is the distance measured in this moving frame of reference. In the present one-dimensional analysis, it is assumed that macroscopic quantities such as the electromagnetic fields and potentials depend only upon \( \xi \), while the density distribution functions \( f \) and \( F \) are functions of \( \xi \) as well as the particle velocities \( v_x, v_y \), and \( v_z \). Thus for

\[ \xi = (z - v_0 t) \quad , \quad (11) \]

Eq. 9a gives

\[ E_x = v_0 \frac{dV_x}{d\xi} \quad , \quad E_y = v_0 \frac{dV_y}{d\xi} \quad \text{and} \quad E_z = -\frac{d\Phi}{d\xi} + v_0 \frac{dV_z}{d\xi} \quad , \quad (12a) \]

and Eq. 9b becomes

\[ B_x = -\frac{dV_y}{d\xi} \quad , \quad B_y = \frac{dV_x}{d\xi} \quad \text{and} \quad B_z = 0 \quad . \quad (12b) \]

It is to be noted that the time-dependent electromagnetic field components are related in the following manner:

\[ E_x B_x + E_y B_y = 0 \quad , \quad (12c) \]
which implies that \( \mathbf{F} \) is perpendicular to \( \mathbf{B} \) spatially.

With the aid of Eqs. 4, Eq. 6a yields

\[
\left(1 - \frac{v^2}{c^2}\right) \frac{d^2A}{dx^2} = -\mu_0 \varepsilon_0 \int \int \int v_x (F - f) dv_x dv_y dv_z ,
\]

\( (13a) \)

\[
\left(1 - \frac{v^2}{c^2}\right) \frac{d^2A}{dy^2} = -\mu_0 \varepsilon_0 \int \int \int v_y (F - f) dv_x dv_y dv_z ,
\]

\( (13b) \)

and

\[
\left(1 - \frac{v^2}{c^2}\right) \frac{d^2A}{dz^2} = -\mu_0 \varepsilon_0 \int \int \int v_z (F - f) dv_x dv_y dv_z ,
\]

\( (13c) \)

whereas Eq. 6b becomes

\[
\left(1 - \frac{v^2}{c^2}\right) \frac{d^2\Phi}{dx^2} = -\frac{\varepsilon_0}{\mu_0} \int \int \int (F - f) dv_x dv_y dv_z
\]

\( (13d) \)

and Eq. 6c gives

\[
\frac{dA_z}{dz} - \frac{v}{c^2} \frac{d\Phi}{d\xi} = 0
\]

\( (13e) \)

where \( c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \) is the speed of light in vacuum.

On the other hand Eq. 1a may be written as follows with the aid of Eqs. 12a and 12b:

\[
u_z \left( \frac{\partial \Phi}{\partial \xi} + \frac{e}{m} \frac{dV}{d\xi} \frac{\partial \Phi}{\partial V_x} + \frac{e}{m} \frac{dV}{d\xi} \frac{\partial \Phi}{\partial V_y} \right)
\]

\[
+ \frac{e}{m} \frac{d}{d\xi} \left( \Phi - v_x V_x - v_y V_y - v_z V_z \right) \frac{\partial \Phi}{\partial u_z} = 0
\]

\( (14a) \)

and Eq. 1b becomes
\[
\begin{align*}
\mathbf{u}_z \left( \frac{\partial F}{\partial \xi} - \frac{e}{M} \frac{dV_x}{d\xi} \frac{\partial F}{\partial V_x} - \frac{e}{M} \frac{dV_y}{d\xi} \frac{\partial F}{\partial V_y} \right) \\
- \frac{e}{M} \frac{d}{d\xi} \left( \phi - v_x V_x - v_y V_y - v_o V_z \right) \frac{\partial F}{\partial u_z} = 0 , \quad (14b)
\end{align*}
\]

where \( u_z = (v_z - u_o) \).

It is not difficult to show that the general solution of

Eq. 14a has the following form:

\[
f(\xi, v_x, v_y, v_z) = \overline{f}(U_x, U_y, W) ,
\]

where \( U_x = [v_x - (e/m)V_x] \),

\[
U_y = [v_y - (e/m)V_y],
\]

\[
W = \frac{1}{2m} \left[ \frac{v_x^2 + v_y^2 + u_z^2}{2} - (U_x^2 + U_y^2) + e(v_o V_z - \phi) \right] \text{ and}
\]

\( \overline{f} \) is an arbitrary differentiable function of its arguments. Similarly, the general solution of Eq. 14b has the form

\[
F(\xi, v_x', v_y', v_z) = \overline{F}(U_{x'i}, U_{y'i}, W_i) ,
\]

where \( U_{x'i} = [v_x + (e/M)V_x] \),

\[
U_{y'i} = [v_y + (e/M)V_y] \text{ and}
\]

\[
W_i = \frac{1}{2m} \left[ \frac{v_x^2 + v_y^2 + u_z^2}{2} - (U_{x'i}^2 + U_{y'i}^2) - e(v_o V_z - \phi) \right] .
\]

It is obvious that once the forms of the distribution functions \( \overline{F} \) and \( \overline{f} \) are known, then the integration in Eqs. 13a-d can be carried out. Thus a set of differential equations governing the potentials \( \overline{A} \) and \( \phi \) can be derived.
Suppose that the distribution functions are of the form

\[ f(U_x, U_y, w) = N e^{\left(\frac{2\pi}{m}\right)^{3/2} \sqrt{\alpha_e \beta_e \gamma_e}} \exp \left[ -\frac{m}{2} (\alpha_e U_x^2 + \beta_e U_y^2) - \gamma_e w \right] \]

and

\[ F(U_{x_1}, U_{y_1}, w_1) = N_1 \left[ \frac{(2\pi)^{3/2}}{M} \sqrt{\alpha_1 \beta_1 \gamma_1} \right] \exp \left[ -\frac{M}{2} (\alpha_1 U_{x_1}^2 + \beta_1 U_{y_1}^2) - \gamma_1 w_1 \right] \]

where

\[ \alpha_e = \frac{1}{K T_{ex}}, \quad \beta_e = \frac{1}{K T_{ey}}, \quad \gamma_e = \frac{1}{K T_{ez}} \]

\[ \alpha_i = \frac{1}{K T_{ix}}, \quad \beta_i = \frac{1}{K T_{iy}}, \quad \gamma_i = \frac{1}{K T_{iz}} \]

with \( K \) denoting the Boltzmann constant, and \( T_x, T_y, \) and \( T_z \) are the temperatures corresponding to the directions along the three coordinate axes. Then upon evaluating the integrals of Eqs. 13a-d, with the aid of Eq. 10, the following set of differential equations is obtained:

\[ (1 - \frac{v_o^2}{c^2}) \frac{d^2 V_x}{d \xi^2} = \mu_0 e_G V_x \]

\[ (1 - \frac{v_o^2}{c^2}) \frac{d^2 V_y}{d \xi^2} = \mu_0 e_G V_y \]
\[
(1 - \frac{v_0^2}{c^2}) \frac{d^2V_x}{dz} = -\mu_0 e_0 \left( N_i e^{-\eta_i} - N_e e^{-\eta_e} \right) \tag{17c}
\]

and
\[
(1 - \frac{v_o^2}{c^2}) \frac{d^2\phi}{dz} = -\frac{e}{\varepsilon_o} \left( N_i e^{-\eta_i} - N_e e^{-\eta_e} \right), \tag{17d}
\]

where
\[
G_x = \left[ \frac{eN_i}{M} \left(1 - \frac{T_{ix}}{T_{iz}}\right) e^{-\eta_i} + \frac{eN_e}{m} \left(1 - \frac{T_{ex}}{T_{ez}}\right) e^{-\eta_e} \right],
\]

\[
G_y = \left[ \frac{eN_i}{M} \left(1 - \frac{T_{iy}}{T_{iz}}\right) e^{-\eta_i} + \frac{eN_e}{m} \left(1 - \frac{T_{ey}}{T_{ez}}\right) e^{-\eta_e} \right],
\]

\[
\eta_i = \frac{1}{kT_{iz}} \left\{ \frac{M}{2} \left[ \left(1 - \frac{T_{ix}}{T_{iz}}\right) \left(\frac{e M V_x}{M V_x}\right)^2 + \left(1 - \frac{T_{iy}}{T_{iz}}\right) \left(\frac{e M V_y}{M V_y}\right)^2 - e(v_0 V_z - \phi) \right] \right\}
\]

and
\[
\eta_e = \frac{1}{kT_{ez}} \left\{ \frac{m}{2} \left[ \left(1 - \frac{T_{ex}}{T_{ez}}\right) \left(\frac{e M V_x}{M V_x}\right)^2 + \left(1 - \frac{T_{ey}}{T_{ez}}\right) \left(\frac{e M V_y}{M V_y}\right)^2 + e(v_0 V_z - \phi) \right] \right\},
\]

where \(N_i\) and \(N_e\) are the constant number densities of ions and electrons respectively in the plasma at some reference point \(\xi = \xi_o\).

The above set of nonlinear ordinary differential equations can be solved in principle once the values of \(V_x, V_y, V_z\) and \(\phi\) and their derivatives with respect to \(\xi\) are specified at \(\xi = \xi_o\). It is of interest to note that the vector potential may be denoted by \(\vec{V} = \vec{A} + \vec{a}\) where \(\vec{a}\) is that part associated with the incident electromagnetic wave and \(\vec{A}\) is that due to the motion of the charged particles in the plasma. Once \(\vec{V}\) and \(\phi\) are known, then the electromagnetic field in the plasma can be obtained from Eqs. 12a and 12b.
For convenience a quantity \( \varphi(\xi) \) is defined by

\[
\varphi(\xi) = \Phi(\xi) - v o V_z(\xi) .
\]  

(18a)

Then

\[
E_z(\xi) = - \frac{d\varphi}{d\xi}
\]

(18b)

and Eqs. 17c and 17d can be combined to give

\[
\frac{d^2\varphi}{d\xi^2} = - \frac{\epsilon}{\epsilon_o} \left( N_i e^{-\eta_i} - N_e e^{-\eta_e} \right)
\]

(18c)

Thus Eqs. 17a, 17b and 18c form a set of nonlinear equations which must be solved for the potential functions. It is of interest to note that when

\[
T_{ex} = T_{ey} = T_{el} \quad \text{and} \quad T_{ix} = T_{iy} = T_{il} ,
\]

(19)

\( G_x \) is equal to \( G_y \), and Eqs. 17a and 17b become respectively

\[
\frac{d^2V_x}{d\xi^2} = R_o V_x \quad \text{and} \quad \frac{d^2V_y}{d\xi^2} = R_o V_y ,
\]

(20)

where

\[
R_o = \frac{1}{(\omega^2 - \nu^2)} \left[ \Omega^2 \left( 1 - \frac{T_{ix}}{T_{iz}} \right) e^{-\eta_i} + \omega^2 \left( 1 - \frac{T_{ez}}{T_{iz}} \right) e^{-\eta_e} \right],
\]

\[
\eta_i = \frac{\epsilon_o}{2N_e KT_{iz}} \left[ \omega^2 \left( 1 - \frac{T_{ix}}{T_{iz}} \right) (\nu^2_x + \nu^2_y) \right] + \frac{\epsilon \nu}{KT_{iz}}
\]

and

\[
\eta_e = \frac{\epsilon_o}{2N_e KT_{iz}} \left[ \omega^2 \left( 1 - \frac{T_{ez}}{T_{iz}} \right) (\nu^2_x + \nu^2_y) \right] - \frac{\epsilon \nu}{KT_{iz}}
\]
with \( \omega_p^2 \equiv (N_e e^2/m_e c_o) \) and \( \Omega_p^2 \equiv (N_i e^2/M_e c_o) \).

Let \( p(\xi) \) be the amplitude and \( \Theta(\xi) \) the spatial angle between the x- and y-components of the transverse magnetic field vector in the system, i.e.,

\[
p(\xi) = \sqrt{B_x^2 + B_y^2} \quad \text{and} \quad \Theta(\xi) = \tan^{-1}\left(\frac{B_y}{B_x}\right);
\]

then, with the aid of Eqs. 20,

\[
\frac{dp}{d\xi} = \frac{R_o(\xi)}{2p(\xi)} \frac{d}{d\xi} \left( V_x^2 + V_y^2 \right) \quad (22a)
\]

and

\[
\frac{d\Theta}{d\xi} = \frac{R_o}{p^2} \left( V_y \frac{dV_x}{d\xi} - V_x \frac{dV_y}{d\xi} \right). \quad (22b)
\]

On the other hand, from Eqs. 20,

\[
\frac{d}{d\xi} \left( V_y \frac{dV_x}{d\xi} - V_x \frac{dV_y}{d\xi} \right) = 0 , \quad (23)
\]

which suggests that

\[
\frac{d\Theta}{d\xi} = \frac{R_o}{p^2} K_1 ,
\]

where \( K_1 \) is independent of \( \xi \), equal to \([V_y(dV_x/d\xi) - V_x(dV_y/d\xi)]\), and can be determined from the values of \( V_x \), \( V_y \), \( dV_x/d\xi \) and \( dV_y/d\xi \) at \( \xi = \xi_o \).

Suppose that the condition of electrical neutrality is satisfied, i.e.,

\[
N_i e^{-\eta_i} = N_e e^{-\eta_e} , \quad N_i = N_e \quad \text{and} \quad \eta_i = \eta_e . \quad (25)
\]
Then the right-hand side of Eq. 18c vanishes so that $E_z$ must be independent of $i$. Although $E_z$ may still contain the electrostatic field, it is assumed to be zero in the present discussion. Consequently $\phi$ is independent of $i$, i.e., $\phi = \phi_0$, a constant, which is taken to be zero for convenience. Thus, under the conditions (Eqs. 25), $R_o$ can be expressed as

$$R_o = -IQ \exp \left[ \frac{1}{2} Q(V_x^2 + V_y^2) \right], \quad (26)$$

where

$$L = \frac{N e}{\varepsilon_0} \frac{(K T e z)}{(c^2 - V_o^2)} \left( 1 + \frac{T_{iz}}{T_{ez}} \right)$$

and

$$Q = \frac{e^2}{m(K T e z)} \left( \frac{T_{iz}}{T_{ez}} - 1 \right).$$

It should be noted that a possible solution of Eq. 23 is the periodic function of $i$, given in the form:

$$V_x = V_0 \sin k(i - i_0) \quad \text{and} \quad V_y = V_0 \cos k(i - i_0), \quad (27)$$

where $k$ and $V_0$ are constant and independent of $i$.

The transverse magnetic field then is obtained from Eq. 12b as

$$B_x = kV_0 \sin k(i - i_0) \quad \text{and} \quad B_y = kV_0 \cos k(i - i_0). \quad (28)$$

Since $i = (z - V_0 t)$ it is easily recognized that this form of solution represents a propagating wave with a propagation constant $k$ and angular frequency $\omega = kV_0$. Furthermore $(V_x^2 + V_y^2) = V_0^2$ is a constant so that $R_o$ is independent of $i$. From Eq. 22a dp/d$i$ = 0, and from Eq. 22b
\( \frac{d\Theta}{d\xi} \) is constant, which implies that the electromagnetic wave propagating in the plasma is a circularly polarized wave. The propagation constant \( k \) of the wave must be so chosen that Eqs. 20 are satisfied. Consequently \( k \) must satisfy the following relationship:

\[
k^2 = \frac{(1/2)QV^2_0}{LQe},
\]

(29a)

which can be written as

\[
(c^2k^2 - \omega^2) = \omega^2_0 \exp\left(\frac{1}{2} \frac{QV^2}{Q_0}\right),
\]

(29b)

where

\[
\omega^2_0 = \omega^2_p \left(1 + \frac{T_{12}}{T_{1e}}\right)\left(\frac{T_{e1}}{T_{1e}} - 1\right).
\]

(29c)

It should be observed that Eq. 29b is simply the dispersion equation for the transverse electromagnetic wave propagating in the plasma.

III. PLASMA IN COMBINED ELECTROSTATIC AND MAGNETOSTATIC FIELDS

Suppose that the externally applied electrostatic and magnetostatic fields are directed along the z-direction. For this case Eqs. 14 must be modified as follows:

\[
u_z \left( \frac{\partial f}{\partial \xi} + \frac{e}{m} \frac{d^2 x}{d\xi^2} \frac{\partial f}{\partial v_x} + \frac{e}{m} \frac{d^2 y}{d\xi^2} \frac{\partial f}{\partial v_y} \right)
\]

\[
+ \frac{e}{m} \frac{d}{d\xi} \left( \phi - v_x y - v_y y - v_{\phi z} \right) \frac{\partial f}{\partial u_z} = \frac{e}{m} B_0 \left( v_x \frac{\partial f}{\partial v_y} - v_y \frac{\partial f}{\partial v_x} \right)
\]

(30a)

and
where $B_o$ denotes a constant applied static magnetic field.

Suppose that a solution of Eq. 30a is looked for in the form:

$$f(v_x, v_y, v_z, \xi) = g(u_z) h(v_x, v_y, \xi), \quad (31)$$

where

$$g(u_z) = g_o \exp \left( -\frac{m}{2KT_{ez}} (u_z - u_o)^2 \right)$$

in which $g_o$ is an arbitrary constant determined by the normalization of the distribution function. $T_{ez}$ and $u_o$ are constants which correspond respectively to the temperature and directed velocity (or drift velocity) along the $z$-axis. Upon substitution of Eq. 31 into Eq. 30a the following set of equations is obtained:

$$\frac{e}{m} B_o \left( v_x \frac{\partial h}{\partial y} - v_y \frac{\partial h}{\partial x} \right) = \frac{e u_o}{KT_{ez}} h \frac{d}{d\xi} \left( \Phi - v_o v_z - v_x v_x - v_y v_y \right) \quad (32a)$$

and

$$\frac{\partial h}{\partial \xi} + \frac{e}{m} \frac{d v_x}{d\xi} \frac{\partial h}{\partial v_x} + \frac{e}{m} \frac{d v_y}{d\xi} \frac{\partial h}{\partial v_y} = \frac{e h}{(KT_{ez})} \frac{d}{d\xi} \left( \Phi - v_o v_z - v_x v_x - v_y v_y \right) \quad (32b)$$

which can also be written in terms of the electromagnetic fields as follows (using Eqs. 12a and 12b):

$$B_o \left( v_y \frac{\partial h}{\partial x} - v_x \frac{\partial h}{\partial y} \right) = -\frac{m u_o}{KT_{ez}} h \left( E_z + v_y B_x - v_x B_y \right) \quad (33a)$$
A possible general solution of Eq. 33a can be written as

\[ h(\xi, v_x, v_y) = h_0(\xi, (v_x^2 + v_y^2)\Psi(v_x, v_y, \xi)) , \]  

where

\[ \Psi(v_x, v_y, \xi) = \exp \left[ \frac{m_i}{(K T_{e z}) B_0} (E_z \theta + v_x B_x + v_y B_y) \right] \]

and

\[ \theta = \tan^{-1} \left( \frac{v_y}{v_x} \right), \]

in which \( h_0 \) is to be determined by substituting Eq. 34 into Eq. 33b. For convenience of calculation Eqs. 33 and 34 are converted into cylindrical coordinates in velocity space by letting

\[ v_x = v_r \cos \theta \quad \text{and} \quad v_y = v_r \sin \theta . \]

In order that Eq. 33b be satisfied identically with respect to \( \theta \) for \( h \) given by Eq. 34, the following conditions must be satisfied:

\[ \frac{dE_z}{\xi} = 0 , \]  

\[ \frac{\partial h_0}{\partial \xi} + \frac{eE_z}{(K T_{e z}) h_0} = 0 , \]

\[ \omega \left( \frac{B}{B_0} \right) \frac{\partial h_0}{\partial v_r} - \frac{e}{K T_{e z}} \left[ \left( \frac{B}{B_0} \right) \left( \frac{U}{v_r} \right) E_z - \frac{u v_r}{\omega_c} \frac{dB}{d\xi} - v \frac{B_y}{v_x} \right] h_0 = 0 \]
where $\omega_c^2 = eB_o/m$ is the electron cyclotron frequency.

If $h_o$ is chosen as

$$h_o(\xi, v^2 + v_e^2) = \exp\left(\frac{e\phi(\xi)}{K T_{ez}} - \frac{m v_e^2}{2K T_{el}}\right), \quad (37)$$

where $\phi(\xi)$ is related to $E_z$ by Eq. 18b, then the function $h$ given by Eq. 34 satisfies Eqs. 33. Thus the distribution function for electrons can be written as follows:

$$f(v_x, v_y, v_z, \xi) = n_e \exp \left[ \frac{-m}{2K T_{ez}} (u_z - u_{oe})^2 - \frac{m}{2K T_{el}} (v_x^2 + v_y^2) \right]$$

$$+ \frac{e\phi}{(K T_{ez})^2} \frac{e}{K T_{ex}} \left( \frac{u_{oe}}{\omega_c} \right) (E_z\theta + v_x B_x + v_y B_y), \quad (38)$$

where $u_z = (v_z - v_e)$ and $n_e$ is an undetermined constant of normalization.

The distribution function for ions can be obtained by replacing $e, m, \omega_c, T_e$ and $n_e$ by $-e, M, -R_c, T_i$ and $n_i$ respectively in Eq. 38:

$$F(v_x, v_y, v_z, \xi) = n_i \exp \left[ \frac{-M}{2K T_{iz}} (u_z - u_{oi})^2 - \frac{M}{2K T_{il}} (v_x^2 + v_y^2) \right]$$

$$- \frac{e\phi}{K T_{iz}} + e \left( \frac{u_{oi}}{\omega_c} \right) (E_z\theta + v_x B_x + v_y B_y). \quad (39)$$

Since the form of the distribution functions has been determined, the integrals of Eqs. 13a-d can, in principle, be evaluated. The calculation of these integrals involves error functions which can be treated approximately under the conditions illustrated below. For the appropriate approximation these integrals can be evaluated analytically.
For convenience, suppose that a factor $\delta$ is defined as

$$\delta = \sqrt{\frac{\mu}{2KT}} \sqrt{\frac{T}{T_z}} \left( \frac{B_\perp}{B_0} \right), \quad (40)$$

where $B_\perp$ denotes the magnitude of the transverse magnetic field and $B_0$ denotes the longitudinal static magnetic field. The first factor represents the ratio of the directed velocity (or drift velocity) in the $z$-direction to the thermal velocity in the same direction, and the second factor is the ratio of the thermal velocity in the transverse direction to that in the longitudinal direction. Then for

$$\delta^3 \ll 1 \quad (41)$$

the components of the electronic current density are given as follows (see Appendix A for details):

$$j_x = K_{\perp} (p_o + p_1 x + p_2 + p_3 x + p_4 y + p_5 y),$$

$$j_y = K_{\perp} (q_0 + q_1 x + q_2 y + q_3 x + q_4 y + q_5 y),$$

$$j_z = K_{\perp} (l_o + l_1 x + l_2 y + l_3 x + l_4 y + l_5 y), \quad (42)$$

where
\[-18-\]

\[
b_x = \frac{B_x}{B_o}, \quad b_y = \frac{B_y}{B_o},
\]

\[
K_1 = \frac{eN_e \sqrt{\pi}}{2\alpha} \left( \frac{1 - e^{2\pi s}}{2\pi} \right) \exp \left( \frac{e\Phi(\xi)}{kT_{ez}} \right),
\]

\[
K_{11} = eN_e \sqrt{\pi} \left( \frac{1 - e^{2\pi s}}{2\pi} \right) \exp \left( \frac{e\Phi(\xi)}{kT_{ez}} \right),
\]

\[
p_0 = \frac{s}{s^2 + 1}, \quad p_1 = \frac{4}{\sqrt{\pi}} \frac{(s^2 + 2) \sigma}{s(s^2 + 4)}, \quad p_2 = \frac{4}{\sqrt{\pi}} \frac{\sigma}{s^2 + 4},
\]

\[
p_3 = \frac{3(s^2 + 7) \alpha^2}{(s^2 + 1)(s^2 + 9)}, \quad p_4 = \frac{-6(s^2 + 3) \alpha^2}{(s^2 + 1)(s^2 + 9)}, \quad p_5 = \frac{6 \alpha^2}{(s^2 + 1)(s^2 + 9)},
\]

\[
q_0 = \frac{-1}{s^2 + 1}, \quad q_1 = -\frac{4}{\sqrt{\pi}} \frac{\alpha}{s^2 + 4}, \quad q_2 = \frac{8}{\sqrt{\pi}} \frac{\sigma}{s(s^2 + 4)},
\]

\[
q_3 = \frac{-3(s^2 + 3) \alpha^2}{(s^2 + 1)(s^2 + 9)}, \quad q_4 = \frac{12 \alpha^2}{(s^2 + 1)(s^2 + 9)}, \quad q_5 = \frac{-18 \alpha^2}{(s^2 + 1)(s^2 + 9)},
\]

\[
l_0 = \frac{1}{s^2 + 1}, \quad l_1 = \frac{\sqrt{\pi} s \alpha}{(s^2 + 1)}, \quad l_2 = -\frac{\sqrt{\pi} \sigma}{(s^2 + 1)},
\]

\[
l_3 = \frac{-2(s^2 + 2) \alpha^2}{s(s^2 + 4)}, \quad l_4 = \frac{4 \alpha^2}{(s^2 + 4)}, \quad l_5 = \frac{-4 \alpha^2}{s(s^2 + 4)},
\]

\[
a^2 = \frac{m}{2kT_{el}}, \quad s = \frac{m}{kT_{ez}} \left( \frac{u_{oe}}{B_o} \right) E_z,
\]

\[
o = \sqrt{\frac{m u_{oe}^2}{2kT_{ez}}} \sqrt{\frac{T_{el}}{T_{ez}}}, \quad \overline{v} = (v_o + u_{oe})
\]

in which \(E_z\) is the z-directed electric field, and \(N_e\) is the electron concentration at the reference point \(\xi = \xi_o\) with \(E_z = 0\).
On the other hand, the components of the ion current density have the same form as the electron current density, namely Eqs. 42, and the coefficients now take the following form (the subscript i is introduced to denote the fact that the quantity is associated with ions):

\[
K_{li} = -\frac{eN_i}{2a_i} \sqrt{\pi} \left( \frac{1 - e^{\frac{-2\pi s_i}{2\pi}}}{2\pi} \right) \exp \left( -\frac{e\phi(t)}{kT_{iz}} \right),
\]

\[
K_{li} = -eN_i \bar{v}_i \left( \frac{1 - e^{\frac{-2\pi s_i}{2\pi}}}{2\pi} \right) \exp \left( -\frac{e\phi(t)}{kT_{iz}} \right),
\]

\[
a_{il}^2 = \frac{M}{2kT_{il}}, \quad s_i = \frac{M}{kT_{iz}} \left( \frac{u_{oi}}{B_o} \right) E_z,
\]

\[
q_i = \sqrt{\frac{M u_{oi}^2}{2kT_{iz}}} \sqrt{\frac{T_{il}}{T_{iz}}}, \quad \bar{v}_i = (v_o + u_{oi}). \quad (44)
\]

Since the current densities of electrons and ions have been determined, with the aid of Eqs. 12a and 12b, Eqs. 13a-d can be written as

\[
\left( 1 - \frac{v_o^2}{c^2} \right) \frac{dB}{dt} = -u_o (j_{xi} + j_{xe}), \quad (45a)
\]

\[
\left( 1 - \frac{v_o^2}{c^2} \right) \frac{dB}{dt} = u_o (j_{yi} + j_{ye}), \quad (45b)
\]

and

\[
\left( 1 - \frac{v_o^2}{c^2} \right) \frac{dE_z}{dt} = \frac{j_{zi}}{\epsilon_o \bar{v}_i} \left( 1 - \frac{v_o}{c^2} \right) + \frac{j_{ze}}{e \bar{v}} \left( 1 - \frac{v_o}{c^2} \right). \quad (45c)
\]

In view of the fact that \(dE_z/dt\) must be zero as suggested by Eq. 36a, the right-hand side of Eq. 45c must vanish. In other words, the following condition must be imposed on the parameters of both ions and electrons:
Furthermore, since $E_z$ is independent of $\xi$, the presence of a uniform static electric field in the $z$-direction is permitted in the present analysis.

The electromagnetic fields in the plasma as a function of $\xi$, can, in principle, be obtained by solving Eqs. 45 with the aid of Eqs. 43 and 44 for properly specified boundary conditions. However, Eqs. 45a and 45b can also be conveniently used to study the effect of the longitudinal static electromagnetic fields on the transverse dynamic magnetic field as illustrated in the following section.

**IV. BEHAVIOR OF TRANSVERSE ELECTROMAGNETIC FIELDS**

Equations 45a and 45b can be written as follows with the aid of Eqs. 43 and 44:

$$\frac{dy}{d\xi} = P_0 + P_1 X + P_2 Y + P_3 X^2 + P_4 XY + P_5 Y^2$$

and

$$- \frac{dX}{d\xi} = Q_0 + Q_1 X + Q_2 Y + Q_3 X^2 + Q_4 XY + Q_5 Y^2,$$

where

$$P_n = \left( C_p e_n,e - C_{1n,1} \right) ,$$

$$Q_n = \left( C_q e_n,e - C_{1n,1} \right) ; \ n = 0, 1, 2, 3, 4 \ and \ 5,$$

$$C_1 = \frac{-1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^2 y}{d\xi^2} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^2 X}{d\xi^2} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^3 y}{d\xi^3} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^3 X}{d\xi^3} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^4 y}{d\xi^4} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^4 X}{d\xi^4} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^5 y}{d\xi^5} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] ,$$

$$\frac{d^5 X}{d\xi^5} = \frac{1}{(e^2 - v_o^2)} \frac{\Omega^2}{\Omega c} \frac{\sqrt{\pi}}{2a_i} \left( \frac{1 - e^{2\pi s_i}}{2\pi} \right) \exp \left[ \left( \frac{eE_o}{kT_{1z}} \right)^2 \right] .$$
in which $E_0$ is a constant longitudinal static field present in the system.

Case I. Static Electric Field-Free Case ($E_0 = 0$).

In this case the coefficients $P$ and $Q$ in Eqs. 47 and 48 all vanish except for $P$ and $Q$ which become equal to one another, so that

$$\frac{dY}{d\xi} = P_{1,o} X \quad \text{and} \quad \frac{dX}{d\xi} = -P_{1,o} Y,$$

where

$$P_{1,o} = \frac{1}{(c^2 - \nu_0^2)} \left( \frac{\omega_p^2}{\omega_c} \frac{g_i}{a_i} - \frac{\omega_p^2}{\omega_c} \frac{g_e}{a_e} \right).$$

Since the coefficients $P_{1,o}$ are independent of $\xi$, the solution of Eq. 50a obviously is a periodic function of $\xi$ and can be written as

$$X = M_0 \cos k_0 (\xi - \xi_0) \quad \text{and} \quad Y = M_0 \sin k_0 (\xi - \xi_0),$$

where $M_0$ and $\xi_0$ are arbitrary constants and the constant $k_0$, which determines the spatial period in the wave frame, yet to be determined, is given by

$$k_0 = \pm P_{1,o}.$$

On the other hand, from Eqs. 36c and 36d (using Eq. 37) one has

$$\frac{dB_Y}{d\xi} + \frac{\omega_c}{u_{oe}} \left( 1 - \frac{T_{ez}}{T_{el}} \right) B_x = 0,$$

$$\frac{dB_X}{d\xi} - \frac{\omega_c}{u_{oe}} \left( 1 - \frac{T_{ez}}{T_{el}} \right) B_y = 0,$$

(52a)
which relate the electron parameters to the transverse magnetic field.

The corresponding set relating the ion parameters to the transverse magnetic field can be obtained by replacing \( \omega_c, T_{ez}, \) and \( T_{el} \) with \(-\omega_c, T_{iz}, T_{il}\) in Eq. 52a. Then in order that the fields obtained from these two sets of equations agree, it is required that

\[
\frac{1}{\mu_{oe}} \left( 1 - \frac{T_{ez}}{T_{el}} \right) = \frac{1}{M_{oi}} \left( \frac{T_{iz}}{T_{il}} - 1 \right).
\]  

(52b)

Furthermore, since the transverse magnetic field components \( B_x \) and \( B_y \) must satisfy both set (50a) and set (52a), the following relationship is established:

\[
P_{1,o} = \frac{eB_o}{\mu_{oe}} \left( \frac{T_{ez}}{T_{el}} - 1 \right).
\]  

(52c)

Suppose that

\[
N_i = N_e \text{ and } u_{oi} = u_{oe};
\]  

(52d)

then by using Eqs. 50b, 51b and 52b, Eq. 52c can be written as

\[
(c^2 - v^2_o) B_o^2 e_o = u_{oe}^2 \left( \frac{T_{il}}{T_{iz}} (MN_i) + \frac{T_{el}}{T_{ez}} (MN_e) \right),
\]  

(52e)

which can also be obtained by equating \( P_{1,o} \) to \( [eB_o/\mu_{oi}(1 - T_{iz}/T_{il})] \).

It is of interest to observe that since \( \xi = (z - v_o t) \), the form of solution given by Eq. 51a appears to an observer in a laboratory frame of reference as a circularly polarized plane wave with a propagation constant \( k_o \) and angular frequency \( \omega = k_o v_o \). The dispersion equation for this mode of propagation is given by Eq. 52e, which can also be written as
\[ (c^2 k^2 \omega_0^2 - \omega^2) = c^2 k^2 \omega_0^2 \left( \frac{\mu_0 \rho_0}{\rho} \right), \]  

(52f)

where

\[ \rho_0 = \left[ M N \left( 1 + \frac{\Delta T}{T_{iz}} \right) + m N \left( 1 + \frac{\Delta T}{T_{ez}} \right) \right], \]  

(52g)

in which

\[ \Delta T_i = (T_{ii} - T_{iz}) \text{ and } \Delta T_e = (T_{ei} - T_{ez}). \]

On the other hand, Eqs. 51 being a parametric representation of a circle in the X-Y plane suggests that the tip of the transverse magnetic field vector denoted by the point \( W(X,Y) \) describes a circle as the parameter \( i \) increases. This picture represents the rotation of the transverse field vector about the z-axis as it propagates along the z-axis. The rate at which the transverse magnetic field vector (or the transverse electric field) rotates per unit distance in \( i \) (in the wave frame) is given by \( k_0 \). For example, given \( \omega \), \( k_0 \) can be determined from Eq. 52f in terms of the system parameters.

The algebraic signs associated with Eq. 51b denote the fact that the plasma is capable of supporting both right-hand and left-hand circularly polarized plane waves. Consequently the electromagnetic wave propagating in a magnetoactive plasma suffers a Faraday rotation, which is to be expected. The angle of rotation \( \varphi_0 \) can be determined by\(^2,3\)

\[ \varphi_0 = \frac{1}{2} (k_{0l} - k_{0r}) d, \]  

(53)

where \( k_{0l} \) and \( k_{0r} \) denote respectively the wave number of the left-hand and right-hand circularly polarized waves, and the distance \( d \) is measured in a laboratory frame.
Case II. Longitudinal Uniform Static Field ($E_0 \neq 0$).

Although the set of nonlinear ordinary differential equations (47) and (48) can be solved numerically for $X(\xi)$ and $Y(\xi)$ by a standard technique such as the Runge-Kutta method, once the values of $X$ and $Y$ are specified at some reference point $\xi = \xi_0$, it is of interest to investigate the following differential equation:

$$\frac{dY}{dX} = \frac{P_0 + P X + P Y + P X^2 + P XY + P Y^2}{Q_0 + Q X + Q Y + Q X^2 + Q XY + Q Y^2}, \quad (54)$$

which is obtained by combining Eqs. 47 and 48.

Suppose that Eq. 46 is satisfied (i.e., $\frac{dE_z}{d\xi} = 0$), which is the case if

$$s_i = s_e = s, \quad \sigma_i = \sigma_e = \sigma \quad (55a)$$

and

$$N_i \left(1 - \frac{y_0 \gamma_i}{c^2}\right) \exp \left[\left(\frac{E_0}{K T_{iz}}\right) \xi\right] = N_e \left(1 - \frac{y_0 \gamma_e}{c^2}\right) \exp \left[-\left(\frac{E_0}{K T_{ez}}\right) \xi\right]. \quad (55b)$$

Then from Eq. 47

$$P_n = (C_e - C_i) p_{n,e} \quad \text{and} \quad Q_n = (C_e - C_i) q_{n,e} \quad (55c)$$

so that Eq. 54 becomes

$$\frac{dY}{dX} = \frac{p(X,Y)}{q(X,Y)}, \quad (56a)$$

where

$$p(X,Y) = P_0 + P_1 X + P_2 X^2 + P_3 X + P_4 XY + P_5 Y^2$$
$$q(X,Y) = Q_0 + Q_1 X + Q_2 Y + Q_3 X^2 + Q_4 XY + Q_5 Y^2, \quad (56b)$$
where $p_n = p_{n,e}$ and $q_n = q_{n,e}$ are given in Eqs. 43 and are independent of $\xi$. The plot of the solution of differential equation (56a) in the $X-Y$ plane gives the desired information with regard to the variation of magnitude and polarization of the transverse magnetic field with the variation of static electric and magnetic fields.

It should be noted that from Eqs. 43

$$\frac{\partial p(X,Y)}{\partial Y} = \frac{\partial q(X,Y)}{\partial X}, \quad (56c)$$

which is the necessary and sufficient condition for Eq. 56a to be an exact differential equation. Therefore the solution of Eq. 56a can be given as

$$p_0 X \left( 1 + \frac{p}{2p_0} X^2 + \frac{p_5}{p_0} Y^2 \right) + q_0 Y \left( 1 + \frac{q}{q_0} X^2 + \frac{q_5}{q_0} Y^2 \right)$$

$$+ \frac{p}{2} X^2 + \frac{q}{q_0} XY + \frac{q_5}{q_0} Y^2 = C, \quad (57)$$

where $C$ is a constant of integration which is to be determined by the value of $X$ and $Y$ at some reference point $\xi = \xi_0$. For example, if $X = 0$ and $Y = Y_0$, then $C$ can be given by

$$C = q_0 Y_0 + \frac{q^2}{2} Y_0^2 + \frac{q^5}{5} Y_0^3. \quad (58)$$

As an illustration Eq. 57 is plotted for a few selected sets of parameters $s$ and $\sigma$ and shown in Figs. 1 through 6.

In view of the fact that $(p_3/p_0)$, $(p_5/p_0)$, $(q_3/q_0)$ and $(q_5/q_0)$ are all less than $\sigma^2$ for an arbitrary value of $s$, if the condition
FIG. 1 PLOT OF Y VS. X FOR \( \sigma = 0.01 \), \( s = 0.1 \), AND \( Y_0 = 0.1, 0.5, 1.0 \).
FIG. 2 PLOT OF Y VS. X FOR \( \sigma = 0.4 \), \( s = 0.4 \), AND \( Y_0 = 0.5, 1.0 \).
FIG. 3 PLOT OF Y VS. X FOR $\sigma = 0.01$, $Y_0 = 1.0$, AND $S = 0.1, -0.1$. 
FIG. 4 PLOT OF Y VS. X FOR $\sigma = 0.01$, $Y_0 = 1.0$, AND $s = 0$, $\pm 0.001$, $\pm 0.01$. 
FIG. 5 PLOT OF Y VS. X FOR $s = 0.1$ AND $Y_0 = 1.0$, WITH $\sigma$ AS A PARAMETER.
FIG. 6 PLOT OF Y VS. X FOR s = 1.0, y_o = 1.0, AND σ = 0.01, 0.4, 1.0.
is satisfied, then Eq. 57 can be reduced to the following second-degree equation:

\[ p_1 x^2 + 2p_2 XY + q_2 Y^2 + 2p_0 X + 2q_0 Y = 2C \quad , \]  

which represents a conic section in the X-Y plane. Since

\[ (p_2^2 - p_1 q_2) = -\frac{16}{\pi} \frac{\sigma_1^2}{s^2} \frac{1}{(s^2 + 4)} \quad , \]  

which is a negative quantity, Eq. 60a represents a family of ellipses. The term in (XY) can be made to vanish in Eq. 60a by a rotation of coordinate axes through an angle \( \tau \), such that

\[ \tan 2\tau = \frac{2p_2}{(p_1 - q_2)} = \left( -\frac{2}{s} \right) \quad . \]  

Upon performing this rotation,

\[ X = X' \cos \tau - Y' \sin \tau \quad , \]
\[ Y = X' \sin \tau + Y' \cos \tau \quad , \]  

and Eq. 60a can be arranged into the following standard form for an ellipse:

\[ \frac{(X' - X_0)^2}{a_0^2} + \frac{(Y' - Y_0)^2}{b_0^2} = 1 \quad , \]  

in which
\[ X'_0 = \frac{-D'}{2A'_1} \quad \text{and} \quad Y'_0 = \frac{-E'}{2C'_1}, \]

where

\[ a'_0^2 = \frac{1}{A'_1} \left( \frac{D'_1^2}{4A'_1} + \frac{E'_1^2}{4C'_1} + F'_1 \right), \]

\[ b'_0^2 = \frac{1}{C'_1} \left( \frac{D'_1^2}{4A'_1} + \frac{E'_1^2}{4C'_1} + F'_1 \right), \]

\[ A'_1 = \frac{2}{\sqrt{\pi}} \left( \frac{g}{s} \right) \left( 1 - \frac{s}{s^2 + 4} \right) \left( 2 \sin 2\tau + s \cos \tau \right), \]

\[ C'_1 = \frac{2}{\sqrt{\pi}} \left( \frac{g}{s} \right) \left( 1 - \frac{s}{s^2 + 4} \right) \left( 2 \sin 2\tau + s \cos \tau \right), \]

\[ D'_1 = \frac{-2}{(s^2 + 1)} \left( \sin \tau + s \cos \tau \right), \]

\[ E'_1 = \frac{2}{(s^2 + 1)} \left( s \sin \tau - \cos \tau \right), \]

\[ F'_1 = \frac{-2Y'_0}{s^2 + 1} + \frac{3}{\sqrt{\pi}} \left( \frac{g}{s} \right) \frac{Y'_0^2}{(s^2 + 4)}. \]

The center of the ellipse is located at the point \((X'_0 = X'_0, Y'_0 = Y'_0)\) and the lengths of the axes of the ellipses are \(2a'_0\) and \(2b'_0\). A typical plot of Eq. 60a is illustrated in Fig. 7.

The desired information in regard to the transverse magnetic field vector can be obtained from Fig. 7; the magnitude and the angle between the \(x\)- and \(y\)-components, which specifies the spatial orientation of the transverse magnetic field vector, are given respectively by \((R\theta)\) and \(\Theta\), where
FIG. 7 PLOT OF $Y$ VS. $X$ BASED ON EQ. 60a FOR $s \neq 0$ AND $3s^2 \ll 1$. 
\[ R = \sqrt{X^2 + Y^2} \text{ and } \Theta = \tan^{-1}\left(\frac{Y}{X}\right), \quad (61) \]

in which \( X \) and \( Y \) are the coordinates of a point \( W(X, Y) \) on the ellipse.

In view of the fact that the ellipse of Eq. 60c can be written parametrically as

\[ X' = X' + a_0 \cos \zeta, \]
\[ Y' = Y' + b_0 \sin \zeta, \quad (62) \]

where the parameter \( \zeta \) is the angle which is to be measured as indicated in Fig. 7, \( R(\zeta) \) and \( \Theta(\zeta) \) can be expressed as

\[ R(\zeta) = \sqrt{(X' + a_0 \cos \zeta)^2 + (Y' + b_0 \sin \zeta)^2} \]
\[ \Theta(\zeta) = \tau + \tan^{-1}\left(\frac{Y' + b_0 \sin \zeta}{X' + a_0 \cos \zeta}\right). \quad (63) \]

\( R(\zeta) \) is a periodic function of \( \zeta \) and has its critical values (maximum or minimum) when \( dR/d\zeta = 0 \), which occurs at \( \zeta = \zeta_c \), such that

\[ \frac{a_0 \sin \zeta_c}{b_0 \cos \zeta_c} = \frac{Y' + b_0 \sin \zeta_c}{X' + a_0 \cos \zeta_c}. \quad (64) \]

Once \( J, s \) and \( Y_0 \) are specified, the quantities \( X'_0, Y'_0, a_0 \) and \( b_0 \) are all determined so that Eq. 64 can be solved for \( \zeta_c \), from which the maximum and minimum values of \( R(\zeta) \) can be obtained. Furthermore it should be noted that as the parameter \( s \) approaches zero, the angle of rotation of the coordinate axes \( \tau \rightarrow -\pi/4 \), so that \( A' \rightarrow (2/\sqrt{\pi})s/\cos, C' \rightarrow (2/\sqrt{\pi})\sin/s, D' \rightarrow -\sqrt{2}, E' \rightarrow -\sqrt{2} \) and \( F' \rightarrow (2/\sqrt{\pi})(s/\cos)Y_0^2 \). Consequently both \( X'_0 \) and \( Y'_0 \) approach zero as of \((-\sqrt{\pi/8})(s/\cos)) \) and both \( a_0 \) and \( b_0 \) approach \( Y_0 \). Therefore Eqs. 63 give
\[ R(\xi) = Y_0 = \text{constant and } \Theta(\xi) = \xi + l\pi + \pi/4, \quad (65) \]

where \( l \) is an integer, and \( X \) and \( Y \) can be given as

\[
X(\xi) = Y_0 \cos [\xi + (l + 1/4)\pi],
\]

\[
Y(\xi) = Y_0 \sin [\xi + (l + 1/4)\pi]. \quad (66)
\]

Thus it is observed that as \( s \to 0 \), the ellipse is gradually deformed into a circle whose center is located at the origin \((X = 0, Y = 0)\) and whose radius is equal to \( a_o = Y_o \).

A comparison of Eqs. 51 and 66 suggests that

\[
\xi = k_0 \xi, \quad \text{for } E_0 = 0. \quad (67)
\]

It should be pointed out that Eq. 67 is valid only if \( E_0 = 0 \). On the other hand, if \( E_0 \) is different from zero, but sufficiently small so that the coefficients \( P \) and \( Q \) in Eqs. 47 and 48 are very slowly varying functions of \( \xi \), then it would not be unreasonable to expect that \( X(\xi) \) and \( Y(\xi) \) will be almost periodic, and to expect the \( W \)-point in Fig. 7 to move along the ellipse as \( \xi \) varies. However, the spatial period in the wave frame is expected to be different from that in the case of \( E_0 = 0 \). It should be noted that under the conditions of Eq. 59, Eqs. 47 and 48 are reduced to the following set of linear equations:

\[
\frac{dY}{d\xi} = P_0 + P_1 X + P_2 Y ,
\]

\[
-\frac{dX}{d\xi} = Q_0 + Q_1 X + Q_2 Y , \quad (68)
\]

in which the coefficients \( P \) and \( Q \) depend upon \( \xi \) in the form of an exponential function: \( \exp [\xi (eE_0/\hbar T_2)\xi] \). For the case where \( E_0 \) is sufficiently small,
the solution of Eqs. 68 may be expected to be almost periodic and its period can be estimated approximately by solving Eqs. 68 as if the coefficients $P$ and $Q$ are independent of $\xi$. In other words, $|e^{E_0/kT_z}\xi| \ll 1$ and $\exp[\mp(e^{E_0/kT_z}\xi)] \approx 1$. Then through a transformation of dependent variables:

\[
X = X'' - \frac{\sqrt{\pi}}{1} \frac{s^2}{\sigma} \frac{1}{(s^2 + 1)},
\]

\[
Y = Y'' + \frac{\sqrt{\pi}}{2} \frac{s}{\sigma} \frac{1}{(s^2 + 1)},
\]

and the set of Eqs. 68 is transformed into the set,

\[
\frac{dY''}{d\xi} = A X'' + B Y''
\]

\[
-\frac{dX''}{d\xi} = C X'' + D Y'',
\]

where

\[
A_1 = \left(\frac{s^2 + 2}{2}\right) Q_2, \quad B_1 = \frac{s}{2} Q_2, \quad C_1 = \frac{-s}{2} Q_2, \quad D_1 = Q_2,
\]

\[
Q_2 = \frac{4}{(s^2 + 4)} \left(1 - e^{2\pi s}/-2\pi s\right) P_{1,0},
\]

in which condition (55a) has been used and $P_{1,0}$ is given in Eq. 50b.

Elimination of $Y''$ from Eqs. 70a and 70b yields

\[
\frac{d^2X''}{d\xi^2} = -K^2X'',
\]

and elimination of $X''$ gives

\[
\frac{d^2Y''}{d\xi^2} = -K^2Y'',
\]
In view of the fact that $K^2$ is a positive quantity, the solutions of Eqs. 71a and 71b are periodic functions of $\xi$ in the wave frame and can be written as

\[ X''(\xi) = M_1 \cos (K_1 \xi + L_1) \]

and

\[ Y''(\xi) = M_2 \cos (K_2 \xi + L_2) , \]

where $M_1, L_1, M_2$ and $L_2$ are arbitrary constants. The constant $K$ is given by

\[ K = \mu(s) \rho_{1,0} \]

where

\[ \mu(s) \equiv \sqrt{\frac{4}{(s^2 + 4)}} \left( \frac{1 - e^{2\pi s}}{2\pi s} \right) . \]  

It should be noted that when $(L_1 - L_2) = \pi/2$, Eqs. 72a and 72b are the parametric equations of an ellipse. Thus the result is an elliptically polarized plane wave in a laboratory frame. Furthermore, if $K_0$ and $\Delta_0$ denote, respectively, the values of $k_0$ and $\psi_0$ which are quantities defined for the case $E_0 = 0$ under the condition stated by Eq. 55a, then the wave number $K$, appearing in Eqs. 72, and the Faraday rotation $\Delta$ for the case $E_0 = 0$ can be expressed as follows:

\[ \frac{K}{K_0} = \mu(s) \text{ and } \frac{\Delta}{\Delta_0} = \mu(s) , \]

where the factor $\mu(s)$ is defined in Eq. 72d. Since $\mu(0)$ equals unity and for $s < 0$, it decreases as $|s|$ increases, Eqs. 73 suggest that the Faraday rotation angle decreases while the wavelength $\lambda = 2\pi/K$ increases with an increase of $|s|$. 

\[ K^2 = \frac{(s^2 + 4)}{4} q_2^2 . \quad (71c) \]
V. DISCUSSION OF RESULTS

For a properly constructed solution of the nonlinear Boltzmann-Vlasov equation in a moving frame of reference, sets of ordinary nonlinear differential equations governing the components of the vector and scalar potentials have been derived; Eqs. 17, for the case where the static electric and magnetic fields are absent, and Eqs. 45 for the case where static electric and magnetic fields are present in the plasma. The numerical analysis of these sets of differential equations is in progress and will be discussed in a future report.

It is of interest, however, to consider a few special cases. For example, in the case of no static fields, with $T_{ex} = T_{ey} = T_{ei}$ and $T_{ix} = T_{iy} = T_{ii}$ and under the condition of electrical neutrality, Eqs. 17 are simplified considerably and could lead to a circularly polarized plane wave solution (Eqs. 27) with a dispersion relationship given by Eq. 29b.

It should be observed that for a real $k$, $\omega$ can be real or complex, depending upon whether $(ck)^2$ is greater or less than $\omega^2 \exp (QV_0^2/2)$, which suggests the possibility of instabilities in the system. It should also be noted that if $T_{ei} \neq T_{ez}$, the wavelength of the transverse electromagnetic wave, $\lambda = 2\pi/k$, does depend upon the amplitude $V_0$ of the wave and is obvious from Eq. 29b. On the other hand, if $QV_0^2/2 \ll 1$, then $\lambda$ becomes independent of the wave amplitude, and Eq. 29b becomes

$$c^2k^2 - \omega^2 = \omega^2_o.$$  \hspace{1cm} (74)

Moreover if $T_{ii} \ll T_{iz}$ and $T_{ei} \ll T_{ez}$, then from Eqs. 25 $T_{iz}/T_{ez} = \Omega^2/\omega^2_p$ so that $\omega^2_o = -\omega^2\Omega^2/\omega^2_p$. Furthermore if the ion motion can also be neglected,
i.e., $T_{iz} \ll T_{ez}$, then $\omega^2 = -\omega_p^2$. Thus Eq. 74 is reduced to a familiar linear dispersion equation\(^8\) for transverse plasma oscillations when no static magnetic field is present.

It should be noted that the set of nonlinear differential equations (47) and (48), governing the behavior of the transverse magnetic field, when there exists longitudinal magnetostatic and electrostatic fields, is derived under the condition that $\delta^3 \ll 1$, where $\delta$ is defined in Eq. 40.

$\delta$ can also be written as $\delta = \sigma R$, where $\sigma = \sqrt{\mu_0 u^2/2kT_z} \sqrt{T_1/T_z}$ and $R = (B_1/B_0)$. The condition $\delta^3 \ll 1$ is not a severe restriction and permits consideration of a wide range of system parameters. However, it should be pointed out that this condition was considered mainly because of mathematical convenience in illustrating the method of analysis. If it were not imposed then the higher-order terms in $b_x$ and $b_y$ would have appeared in the current density expressions of Eqs. 42 as well as in Eqs. 47 and 48.

It has been shown that in the absence of a longitudinal static electric field the plasma can support circularly polarized plane waves, whose dispersion relation is given by Eq. 52f under the condition of electrical neutrality. For a plasma whose mean velocity along the z-axis vanishes (i.e., $\bar{v} = 0$, or $v_0 = -v_0$) and which exhibits a small temperature anisotropy, $\Delta T_e \ll T_{ez}$ and $\Delta T_i \ll T_{iz}$, $\rho_0$, given in Eq. 52g, becomes $(\rho_0 n_i + \rho_0 n_e)$, which is the mass density of the plasma. Consequently Eq. 52f can be written as

$$\omega^2 = \frac{c^2 \omega_0^2}{\left(1 + \frac{c^2}{v_A^2}\right)}; \quad v_A \equiv \sqrt{\frac{B_0^2}{\mu_0 \rho_0}},$$

(75)
where \( v_A \) is the Alfven velocity and Eq. 75 is recognized as the dispersion relation for the Alfven waves\(^{21}\).

On the other hand, from Eqs. 50b and 51b,

\[
c^2 k_z^2 - \omega^2 = \pm \frac{\omega}{\omega_c} \left( \frac{u_{oe}}{v_o} \right) \omega_p^2 \left[ \left( \frac{N_i u_{oi}}{N_e u_{oe}} \right) \frac{T_{iz}}{T_{iz}} - \frac{T_{ez}}{T_{ez}} \right]. \quad (76a)
\]

For a plasma under the condition of quasi-electrical neutrality, i.e., \( N_i u_{oi} \approx N_e u_{oe} \), and vanishing mean velocity along the z-axis (i.e., \( v = 0 \)), the refractive index \( n \) can be expressed as

\[
n^2 = 1 \pm \frac{\omega_p^2}{\omega \omega_c} \left( \frac{T_{iz}}{T_{iz}} - \frac{T_{ez}}{T_{ez}} \right), \quad (76b)
\]

which is recognizable as the dispersion relation from magnetoionic theory for \( \omega \ll \Omega_c < \omega_c \). Thus it appears that Eq. 52f or Eq. 76a may be profitably applied to the investigation of some ionospheric phenomena, such as VLF emissions and whistler mode propagation in ionospheric plasmas.

It has also been shown that for the case where a longitudinal static electric field is present (i.e., \( E_o \neq 0 \)), the magnitude of the transverse magnetic field no longer remains invariant, as in the case of \( E_o = 0 \), but varies with distance in the wave frame. Under the condition \( \delta^3 \ll 1 \), the x- and y-components of the magnetic field vector are related by Eq. 57 and the tip of the magnetic field vector describes the curves as illustrated in Figs. 1 through 6. However, under the small-amplitude condition of Eq. 59, except for extremely small values of \( \sigma \), the locus of the tip of the magnetic field vector describes an ellipse as shown in Fig. 7. It is observed that the magnitude of the normalized transverse magnetic field...
vector \( \mathbf{R} = (B_i/B_o) \) varies between its minimum and maximum values in a wave frame as \( \xi \) varies, and that as \( s \to 0 \), the ellipse is gradually deformed into a circle. Furthermore, under condition (59) for the region \( |eE_o/\omega/kT_2| \ll 1 \), it is shown that the solution of Eqs. 47 and 48 is a periodic function of \( \xi \), as given by Eqs. 72 and the tip of the magnetic field vector describes an ellipse in a wave frame. Thus it is observed that the transverse electromagnetic wave in the presence of a weak static longitudinal electric field can propagate along the static longitudinal magnetic field as an elliptically polarized plane wave with the magnitude of the rotating magnetic field vector varying periodically with distance \( z \). Therefore the amplitude and phase of a circularly polarized plane wave propagating in a magnetoactive plasma is modified by the presence of a longitudinal static electric field. The modification of the wavelength \( \lambda \) and the Faraday rotation angle, \( \Delta \), due to a weak static electric field \( E_o \) is given in Eqs. 73 and is valid for an arbitrary value of the parameter \( s \). An examination of Eqs. 73 reveals that the Faraday rotation angle \( \Delta \) tends to decrease, while the wavelength \( \lambda \) increases, with an increase of \( \vert s \vert \). It is of interest to note that since \( s \) is defined as \( [(\mu_o/\kappa T_2)(E_o/B_o)] \), an increase in \( B_o \) will cause \( \vert s \vert \) to decrease, \( \Delta \) to increase and \( \lambda \) to decrease, which is considered reasonable.
APPENDIX A. DERIVATION OF EQUATIONS 42 AND 43

For the electron distribution function given by Eq. 38, the electron current density components may be given as

\[ j_x = L_0 \int_0^{2\pi} I_2(\theta) \cos \theta \, e^{s\theta} \, d\theta, \]

\[ j_y = L_0 \int_0^{2\pi} I_2(\theta) \sin \theta \, e^{s\theta} \, d\theta, \]

\[ j_z = L_1 \int_0^{2\pi} I_1(\theta) \, e^{s\theta} \, d\theta, \]

(A.1)

where

\[ L_0 = -n_e e \exp \left( \frac{e\phi}{kTz} \right) \int_{-\infty}^{\infty} e^{-\frac{m}{2kTz}(v_z - \bar{v})^2} \, dv_z = -\sqrt{\pi} \sqrt{\frac{2kTz}{m}} n_e e \exp \left( \frac{e\phi}{kTz} \right), \]

\[ L_1 = -n_e e \exp \left( \frac{e\phi}{kTz} \right) \int_{-\infty}^{\infty} v_z e^{-\frac{m}{2kTz}(v_z - \bar{v})^2} \, dv_z = \bar{v}L_0, \]

\[ I_1(\theta) = \int_0^{\infty} v_r \exp \left[ -\frac{m}{2kTz} \left( (v_r - \beta)^2 - \beta^2 \right) \right] \, dv_r, \]

\[ I_2(\theta) = \int_0^{\infty} v_r^2 \exp \left[ -\frac{m}{2kTz} \left( (v_r - \beta)^2 - \beta^2 \right) \right] \, dv_r, \]

\[ s = \frac{m}{kTz} \left( \frac{u_0}{B_0} \right) E_z \]

and

-43-
\[ \beta(\theta) \equiv \left( \frac{T_{e1}}{T_{ez}} \right) \left( \frac{u_o}{B_o} \right) \left( B_x \cos \theta + B_y \sin \theta \right) \]
\[ = u_o \left( \frac{T_{e1}}{T_{ez}} \right) \left( \frac{B_1}{B_o} \right) \cos (\theta - \theta) , \]

where
\[ B_1 = \sqrt{B_x^2 + B_y^2} \text{ and } \Theta = \tan^{-1} \left( \frac{B_y}{B_x} \right) . \] (A.2)

\[ I_1(\theta) \text{ and } I_2(\theta) \text{ can be evaluated to give} \]
\[ I_1(\theta) = \frac{1}{2a^2} \left[ 1 + \sqrt{\pi} \gamma e^{\gamma^2} \text{erfc} (\gamma) \right] , \]
\[ I_2(\theta) = \frac{1}{2a^3} \left[ 3\gamma + \left( \frac{1}{2} + \gamma^2 \right) \sqrt{\pi} \ e^{\gamma^2} \text{erfc} (\gamma) \right] , \] (A.3)

where
\[ a^2 = \left( \frac{m}{2KT_{el}} \right) , \quad \gamma = (a\beta) , \]
\[ \text{erfc} (\gamma) = \frac{2}{\sqrt{\pi}} \int_{-\infty}^{D} e^{-t^2} dt = [1 - \text{erf}(\gamma)] , \] (A.4)

in which \( \text{erf}(\gamma) \) is the usual error function.

It is well known that the function \( \text{erf}(\gamma) \) can be expanded into a power series in \( \gamma \) (e.g., see Dwight22, p.129):
\[ \text{erf} (\gamma, = \frac{2\gamma}{\sqrt{\pi}} \left( 1 - \frac{\gamma^2}{1!3} + \frac{\gamma^4}{2!5} - \frac{\gamma^6}{3!7} + ... \right) , \quad \gamma^2 < \infty . \]

For cases in which \( \gamma^3 \ll 1 \) (e.g., \( \gamma^3 = 0.01 \), which is equivalent to \( \gamma_0 \approx 0.217 \)), for \( \gamma < \gamma_0 \),
erfc (γ) ≈ \left[ 1 - \frac{2γ}{\sqrt{π}} \left( 1 - \frac{γ^2}{3} \right) \right]

so that I_1 (θ) and I_2 (θ) can be approximated as

I_1 (θ) = \frac{1}{2a^2} \left( 1 + \sqrt{π}γ - 2γ^2 \right),

I_2 (θ) = \frac{\sqrt{π}}{4a^3} \left( 1 + \frac{4γ}{\sqrt{π}} + 3γ^2 \right).

(A.6)

Since γ can also be written conveniently as

γ = δ \cos (θ - φ),

(A.7)

where

δ = \sqrt{\frac{μv_0^2}{2κT_0}} \sqrt{\frac{Te_1}{5ez}} \left( \frac{B}{B_0} \right),

the condition γ^3 ≪ 1 implies that

δ^3 ≪ 1.

(A.8)

On the other hand γ can also be written as

γ = (ατ)(B_x \cos θ + B_y \sin θ),

(A.9)

where

τ = \left( \frac{Te_1}{Tez} \right) \left( \frac{u_o}{B_0} \right).

Substituting I_1 (θ) and I_2 (θ), given by Eq. A.6, into Eqs. A.1 and carrying out the integration yields
\[
\begin{align*}
\mathbf{j}_x &= \frac{\sqrt{\pi}L_0}{4a^3} \left[ C_1^1 + \left( \frac{4\pi r}{\sqrt{\pi}} \right)^2 B_x + \left( \frac{4\pi r}{\sqrt{\pi}} \right)^2 S_1^2 \right] B_y \\
&\quad + 3(a^2 + c^2) B_x^2 + 6a^2 + 2^2 (c_1 - c_3) B_x B_y + 3a^2 + 2^2 (c_1 - c_3) B_y^2 \\
\mathbf{j}_y &= \frac{\sqrt{\pi}L_0}{4a^3} \left[ S_1^1 + \left( \frac{4\pi r}{\sqrt{\pi}} \right)^2 B_x + \left( \frac{4\pi r}{\sqrt{\pi}} \right)^2 S_1^2 \right] B_y \\
&\quad + 3a^2 + 2^2 (c_1 - c_3) B_x^2 + 6a^2 + 2^2 (c_1 - c_3) B_x B_y + (3a^2 + 2^2 S_1^1) B_y^2 \\
\mathbf{j}_z &= \frac{L_0}{2a^2} \left[ \left( \frac{1 - e^{2\pi s}}{s} \right) + (\sqrt{\pi} a^2 c_1^1) B_x + (\sqrt{\pi} a^2 S_1^1) B_y \\
&\quad - \left( 2a^2 + 2^2 c^2 \right) B_x^2 - \left( 2a^2 + 2^2 s_1^1 \right) B_x B_y - \left( 2a^2 + 2^2 s_1^1 \right) B_y^2 \right], \quad (A.10)
\end{align*}
\]

where

\[
\begin{align*}
C_1^1 &= \int_0^{2\pi} \cos \theta e^{s\theta} d\theta = \frac{-s}{s^2 + 1} (1 - e^{2\pi s}), \quad (A.11a) \\
C_1^2 &= \int_0^{2\pi} \cos^2 \theta e^{s\theta} d\theta = \frac{-s + 2}{s} (1 - e^{2\pi s}), \quad (A.11b) \\
C_1^3 &= \int_0^{2\pi} \cos^3 \theta e^{s\theta} d\theta = \frac{-1 - e^{2\pi s}}{(s^2 + 9)} \left( s + \frac{6s}{s^2 + 1} \right), \quad (A.11c) \\
S_1^1 &= \int_0^{2\pi} \sin \theta e^{s\theta} d\theta = \frac{1}{s^2 + 1} (1 - e^{2\pi s}), \quad (A.11d) \\
S_1^2 &= \int_0^{2\pi} \sin^2 \theta e^{s\theta} d\theta = \frac{-2}{s(s^2 + 4)} (1 - e^{2\pi s}), \quad (A.11e)
\end{align*}
\]
\[ S^3 = \int_0^{2\pi} \sin^3 \theta e^{i\theta} d\theta = \frac{(1 - e^{2\pi s})}{(s^2 + 9)} \frac{6}{(s^2 + 1)} , \quad (A.11f) \]

\[ S^1 = \int_0^{2\pi} \sin 2\theta e^{i\theta} d\theta = \frac{2}{(s^2 + 4)} (1 - e^{2\pi s}) . \quad (A.11g) \]

Defining

\[ b_x = \frac{B x}{B_0} , \quad b_y = \frac{B y}{B_0} \quad \text{and} \quad \sigma = \sqrt{\frac{\mu u^2}{2KT_e z}} \sqrt{\frac{T_e}{T_z}} , \quad (A.12) \]

the factors \((atB_x)\) and \((atB_y)\) appearing in Eq. A.10 can be respectively replaced by \((ob_x)\) and \((ob_y)\), so that

\[ j_x = K_1 (p_o + p_1 b_x + p_2 b_y + p_3 b^2 x + p_4 b x y + p_5 b^2 y) , \]

\[ j_y = K_1 (q_o + q_1 b x + q_2 b y + q_3 b^2 x + q_4 b x y + q_5 b^2 y) , \]

\[ j_z = K_{|z|} (l_0 + l_1 b x + l_2 b y + l_3 b^2 x + l_4 b x y + l_5 b^2 y) , \quad (A.13) \]

where

\[ K_1 = \frac{\sqrt{\pi}}{4 \pi^2} L_o (e^{2\pi s} - 1) , \]

\[ K_{|z|} = \frac{1}{2 a^2} (e^{2\pi s} - 1) , \quad (A.14a) \]

\[ p_o = \frac{s}{(s^2 + 1)} , \quad p_1 = \frac{4}{\sqrt{\pi}} \frac{(s^2 + 2)}{(s^2 + 4)} \frac{s}{s} , \quad p_2 = - \frac{4}{\sqrt{\pi}} \frac{\sigma}{(s^2 + 4)} , \]

\[ p_3 = \frac{(s^2 + 7)}{(s^2 + 9)} \frac{3 s^2}{(s^2 + 1)} , \quad p_4 = \frac{(s^2 + 3)}{(s^2 + 9)} \frac{6 s^2}{(s^2 + 1)} , \quad p_5 = \frac{6}{(s^2 + 9)} \frac{s^2}{(s^2 + 1)} , \quad (A.14b) \]
\[
q_0 = \frac{-1}{(s^2+1)}, \quad q_1 = \frac{-4}{\sqrt{\pi}} \frac{\sigma}{s(s^2+4)}, \quad q_2 = \frac{4}{\sqrt{\pi}} \frac{2\sigma}{s(s^2+4)},
\]
\[
q_3 = \frac{-3\sigma^2}{(s^2+3)(s^2+1)}, \quad q_4 = \frac{12}{(s^2+9)(s^2+1)}, \quad q_5 = \frac{-18\sigma^2}{(s^2+9)(s^2+1)},
\]
(A.14c)
\[
l_0 = \frac{1}{s}, \quad l_1 = \sqrt{\pi} \frac{s}{(s^2+1)} \sigma, \quad l_2 = -\sqrt{\pi} \frac{1}{(s^2+1)} \sigma,
\]
\[
l_3 = -\frac{2(s^2+2)}{s(s^2+4)} \sigma^2, \quad l_4 = \frac{4}{(s^2+4)} \sigma^2, \quad l_5 = \frac{-4}{s(s^2+4)} \sigma^2. \quad (A.14d)
\]

By substituting the values of \( L_0 \) and \( L_1 \) into the expressions for \( K_1 \) and \( K_1' \), and if the distribution function \( f \) is normalized to a constant density \( N_e \), with \( E_0 = 0 \), \( K_1 \) and \( K_1' \) can be expressed as
\[
K_1 = \frac{eN\sqrt{\pi}}{2\sigma} \left( \frac{1 - e^{2\pi s}}{2\pi} \right) \exp \left( \frac{e\varphi}{kT_{ez}} \right),
\]
\[
K_{1'} = \frac{eN\sqrt{\pi}}{2\sigma} \left( \frac{1 - e^{2\pi s}}{2\pi} \right) \exp \left( \frac{e\varphi}{kT_{ez}} \right). \quad (A.15)
\]

Thus Eqs. 42 and 43 are obtained.
LIST OF REFERENCES


-49-


