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REFLECTION AND TRANSMISSION OF ELECTROMAGNETIC WAVES ON THE INTERFACE BETWEEN VACUUM AND MAGNETIZED PLASMA

B. M. JOVANOVIĆ

Institute of Physics, Faculty of Medicine, University of Niš, P.O.B. 174, 18001 Niš
E–mail braca95@medfak.medfak.ni.ac.yu

Abstract. The phenomena of reflection and transmission of plane electromagnetic waves on the plane interface are studied. Vacuum is the first medium and homogeneous, collisionless magnetized plasma is the second one. On the base of boundary conditions the reflection and transmission coefficients are obtained analytically and their numerical calculating results are presented as well. Specially, the dependence of these coefficients on various plasma and incident radiation parameters are considered.

1. INTRODUCTION

The problem of propagating of electromagnetic waves through the vacuum -plasma system is interesting not only for theoretical investigations (Čadež and Jovanović, 1996; Sauer and Baumgartel, 1982; Born and Wolf, 1968; Benz, 1993), but for practice (Ginzburg, 1967) too. This is particularly topical in radio astronomy, when the source is located on the Earth or on the other heavenly bodies (Sun, Stars etc.).

In this paper the plasma medium is assumed homogeneous with negliable thermal and dissipative effects on the wave processes. It is placed in half-space with constant external magnetic fields. The reflection and transmission coefficients are introduced as it was done by Born (Born and Wolf, 1968). These quantities are calculated for different electron densities and magnetic field intensities at given location within the considered plasma as well as for various initial wave frequences, polarization and propagation angles with respect to the external magnetic field.

The obtained results can be used as a tool for diagnostics of stellar atmospheres, for making models of radio emission sources as well as for giving explanations about the polarization of solar radio emission.

2. BASIC EQUATIONS

The electric field of the incident electromagnetic wave in vacuum ($x < 0$) is given by:

$$\vec{E}^i(x,t) = [A_y(x)\vec{e}_y + A_z(x)\vec{e}_z]e^{-i(\omega t - k^i x)}. \tag{1}$$

Some of this radiation is reflected back into the medium of incidence and some is transmitted across the plane interface. The electric fields of the reflected and transmitted waves are given by

$$\vec{E}^r(x,t) = [A_y^r(x)\vec{e}_y + A_z^r(x)\vec{e}_z]e^{-i(\omega t + k^i x)}, \tag{2}$$

$$\vec{E}^t = \vec{E}_o^{(1)} + \vec{E}_e^{(1)} = \vec{A}_o^{(1)} e^{-i(\omega t - k_o^{(1)} x)} + \vec{A}_e^{(1)} e^{-i(\omega t - k_e^{(1)} x)}, \tag{3}$$

where the first term on the right side of relation (3) corresponds to the ordinary mode and the second one to the extraordinary mode.

Taking into account the expressions for incident, reflected and transmitted time averaged energy fluxes

$$< S_x^i >= \frac{c\epsilon_0}{2}|A|^2, \quad < S_x^r >= \frac{c\epsilon_0}{2}|A^r|^2, \quad < S_x^t >= \frac{c^2\epsilon_0}{2} R_e(E_y^t B_z^{t^*} - E_z^t B_y^{t^*}), \tag{4}$$

as well as for the electric fields (expressions (2) and (3)), one can obtain the following relations for the reflection and the transmission coefficients (Born and Wolf, 1968):

$$\begin{aligned}
R = {} & [(1 + N_o^{(1)})^2 (1 + N_e^{(1)})^2 (B_1 - B_2)^2]^{-1} \Big\{ \Big(4(N_e^{(1)} - N_o^{(1)})^2 + \\
& + [B_1(1 + N_e^{(1)})(1 - N_o^{(1)}) + B_2(1 + N_o^{(1)})(N_e^{(1)} - 1)]^2 \Big) \sin^2\Phi + \\
& + \Big(4B_1^2 B_2^2 (N_o^{(1)} - N_e^{(1)})^2 + [B_1(1 + N_o^{(1)})(1 - N_e^{(1)}) + \\
& + B_2(1 + N_e^{(1)})(N_o^{(1)} - 1)]^2 \Big) \cos^2\Phi \Big\} \\
T_o = {} & \frac{4N_o^{(1)}(B_2^2\cos^2\Phi + \sin^2\Phi)(1 + B_1)}{(1 + N_o^{(1)})^2 (B_1 - B_2)^2} \\
T_e = {} & \frac{4N_e^{(1)}(B_1^2\cos^2\Phi + \sin^2\Phi)(1 + B_2)}{(1 + N_e^{(1)})^2 (B_1 - B_2)^2} \\
T_{oe} = {} & -\frac{4(N_o^{(1)} + N_e^{(1)})(1 + B_1 B_2)(B_1 B_2^2 \cos^2\Phi + \sin^2\Phi)}{(1 + N_o^{(1)})(1 + N_e^{(1)})(B_1 - B_2)^2}.
\end{aligned} \tag{5}$$

The polarization angle Φ is defined as the dary ($x = 0$) and the normal to the plane specified by external magnetic field $\vec{B}_0(\vec{B}_0 = B_{0x}\vec{e}_x + B_{0z}\vec{e}_z))$ and the wave vector $\vec{k}$. $N_o^{(1)}$ and $N_e^{(1)}$ are the refractive indices related to the ordinary and the extraordinary mode respectively. The coefficients B_1 and B_2 follow from the relations

$$\begin{aligned}
A_{oz}^{(1)}(0) &= -i\frac{2(1-v)\sqrt{u}\cos\theta}{u\sin^2\theta - \sqrt{u^2\sin^4\theta + 4u(1-v)^2\cos^2\theta}} A_{oy}^{(1)}(0) \equiv \beta_1 A_{oy}^{(1)}(0) \\
A_{ez}^{(1)}(0) &= -i\frac{2(1-v)\sqrt{u}\cos\theta}{u\sin^2\theta + \sqrt{u^2\sin^4\theta + 4u(1-v)^2\cos^2\theta}} A_{ey}^{(1)}(0) \equiv \beta_2 A_{ey}^{(1)}(0),
\end{aligned} \tag{6}$$

where θ is the angle between the vectors $\vec{B}_0$ and $\vec{k}$, and parameters u and v are given by

$$u = (\frac{\omega_c}{\omega})^2, \quad v = (\frac{\omega_p}{\omega})^2. \qquad (7)$$

The transmission coefficient T_{oe} coresponds to the interaction of ordinary and extraordinary waves. The coefficients in (5) are obtained supposing that plasma is transparent for ordinary and extraordinary modes. The other cases, when one of modes cannot propagate through plasma, are investigated in Jovanović (1994).

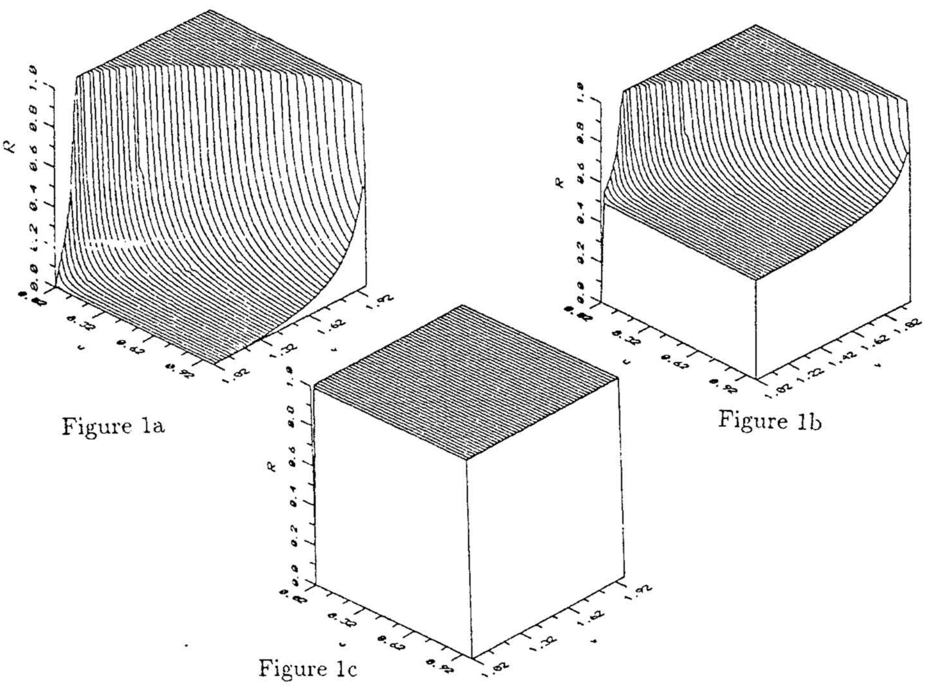

Figure 1a

Figure 1b

Figure 1c

Fig. 1. Reflection coefficient as function of parameters $\frac{\omega_c^2}{\omega^2}$ and $\frac{\omega_p^2}{\omega^2}$ for $\theta = 90°$ and three different values of angle Φ : 0° (Fig. 1a), 45° (Fig. 1b) and 89° (Fig. 1c).

3. NUMERICAL RESULTS

Figures 1a,1b and 1c present the reflection coefficient R as function of external magnetic field (parameter u) and plasma density (parameter v) for three values of polarization angle Φ. The other parameters are constant and given at the foot of Figures. One can notice that the reflection is total ($R = 1$) in wide region of parameters u and v for $\Phi = 0^0$ and $\Phi = 45^0$, but for $\Phi = 89^0$ in the empty region ($0 < u < 1$ and $1 < v < 2$), coefficient $R = 1$. It means that propagation of the both modes in plasma is impossible for $\Phi \approx 90^0$ (see Figure 2c). Figures 2a,2b and 2c represent the dependence of transmission coefficient of extraordinary mode on parameters u and v.

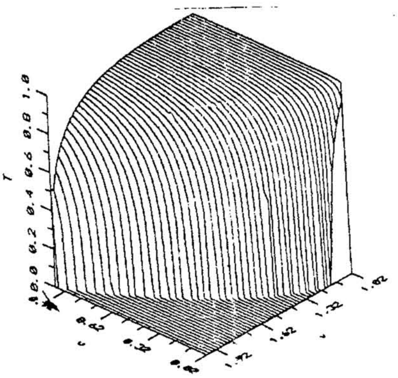

Figure 2a

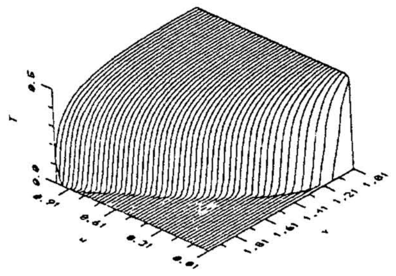

Figure 2b

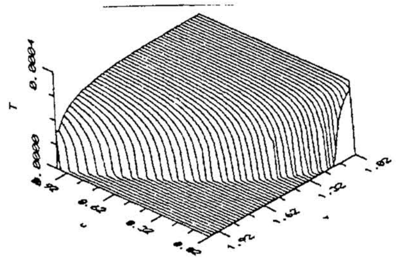

Figure 2c

Fig. 2. Transmission coefficient of extraordinary wave as function of parameters $\frac{\omega_c^2}{\omega^2}$ and $\frac{\omega_p^2}{\omega^2}$ for $\theta = 90°$ and three different values of angle Φ : 0° (Fig. 2a), 45° (Fig. 2b) and 89° (Fig. 2c).

As it is known, the conservation of energy can be given by the sum $R + T_e + T_o = 1$, making possible to find coefficient T_o if R and T_e are known. According to that low, one can see that maximum propagation of ordinary mode is obtained for $\Phi = 0, u \rightarrow 0$ and $v \rightarrow 2$.

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