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Cherenkov Effect in Ionospheric E Layer Plasma for Oxygen-Ion

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Authors' contributions

Both mentioned above Authors carried out this work together.

Research Article

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ABSTRACT

Cherenkov radiation is an electromagnetic Radiation that occurs in different medium depending on the physical properties of the medium". The sufficient scientific condition for the phenomenon to be occurred is that the velocity of charged particles moving with should be greater than that of the electromagnetic radiation there (generally speaking in most cases this Radiation is in the UV range of emission depending on the particles velocity and yet again the properties of the medium"). In this paper Cherenkov effect considered in the ionospheric E layer plasma and it showed that the velocity of charged particles in this plasma is greater than that of the phase velocity of electromagnetic radiation. Then the relation between Cherenkov frequency and the height and temperature of this plasma studied. Also the Cherenkov angle for the oxygen ion that emits Cherenkov radiation is calculated. In this plasma as an important wave we considered only the oxygen-ion wave.

Keywords*: Cherenkov radiation; ionospheric E layer plasma; oxygen-ion wave; UV frequency.*

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1. INTRODUCTION

Cherenkov radiation was first observed in the early 1900's by the experiments developed by Mary and Pierre Curie when studying radioactivity emission. The first attempt to understand the phenomenon was made by Mallet in 1926. He found that the light emitted from a wide variety of transparent bodies placed close to a radioactive source always had the same bluish-white quality, and the spectrum was continuous,that is not possessing the line or band structure characteristic of fluorescence. Mallet found that the nature of such emission is not be known yet. It was not until the experimental work carried out between years 1934-1937 by P. A. Cherenkov and the theoretical interpretation by I. E. Tamm and I. M. Frank (1937) that this radiation was described. Cherenkov light in the atmosphere is produced by charged particles traveling faster than the speed of the light in medium.

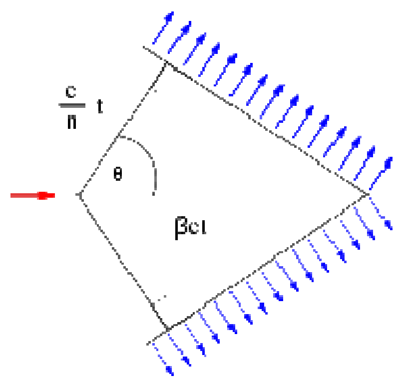

Fig. 1. Path of Cherenkov emission [1]

From Fig. 1. it is understood that this radiation is only observed at a particular angle Θ called Cherenkov angle, with respect to the track of the particle. This angle represents the position in which waves from arbitrary point such as P1, P2 and P3 over the track AB are coherent and combine to form a plane wave front BC. This coherence takes place when the particle travels from A to B in the same time that the light travels from A to C. If the velocity of the particle is v or β.c where c is the velocity of light in vacuum, and c/n is the velocity of the Cherenkov light in the medium, then we can write the Cherenkov angle in the following way with only taking into account the geometrical considerations

$$cos\theta = \frac{\frac{c}{n(\lambda)}\Delta T}{\beta.C\Delta T} \quad (1\text{-}1)$$

$$cos\theta = \cos\theta = \frac{1}{\beta.n(\lambda)} \quad (1\text{-}2)$$

where n is the refractive index of the medium and ΔT is the time in which the particle moves from A to B.

The number of photons emitted by a charged particle of charge **ze** per unit path length, per unit energy interval, in term of λ, of the photons is equal to the following, which is obvious from Fig. 2:

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) \tag{1-3}$$

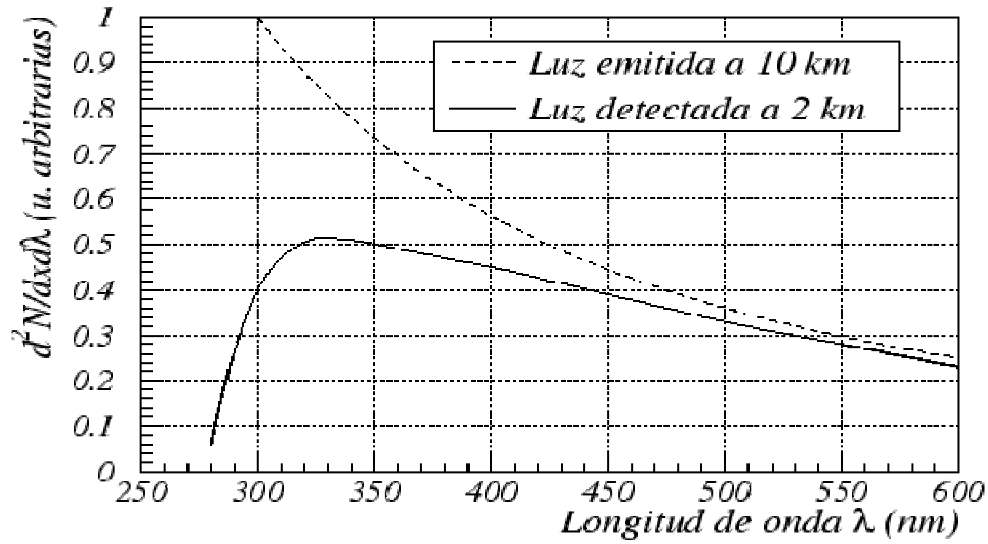

Fig. 2. Differential Cherenkov photon spectrum. Continuous line includes absorption by ozone and Rayleigh and Mie scattering [2]

where α is the micro structure constant $\alpha = \frac{e^2}{hc} = \frac{1}{137}$ and *n* is the refraction index of the medium that is a function of the photon energy, straight foreward to λ. This means that most part of Cherenkov photons are emitted in the ultraviolet range, because:

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2}$$

and the spectrum has a peak at around 330 nm [3].

In ionosphere from 90 kilometer of earth surface up to 120 kilometer of earth surface the E layer occured that in this medium the oxygen ionization take place with solar x ray and uv radiation respectively.

Because the plasma is a quasi-neutral gas with equale electrons and ions particles together with neutral species, then the E layer also is a plasma medium so as we can use the plasma equations for the parameters inside.

2. EQUATIONS

We use the MHD approximation specially when the orientation of motion for ion is parallel to magnetic field, then this would be:

$$Mn\left[\frac{\partial v_i}{\partial t} + (v_i \cdot \nabla)vi\right] = enE - \nabla p \tag{2-1}$$

With consideration of:

$$E = -\nabla\varphi , \qquad , \qquad ik\hat{x} = \nabla \qquad , \qquad -i\omega = \frac{\partial}{\partial t}$$
$$n_e = n_0 + n_1 \quad , \quad v_e = v_0 + v_1 \quad , \quad E = E_0 + E_1$$

That in these equations, index 1 shows the turbulence state.
So we have:

$$-i\omega M n_0 v_{1i} = -en_0 ik\varphi - \gamma_i kT_i in_1 \qquad (2\text{-}2)$$

Also from Boltzmann equation it is true that:

$$\mathrm{n_e} = \mathrm{n_0} \mathrm{e}^{\frac{\mathrm{e}\varphi}{\mathrm{KTe}}} \rightarrow \mathrm{n_e} = \mathrm{n_0}\left(1 + \frac{\mathrm{e}\varphi_1}{\mathrm{KT_e}}\right) \rightarrow \mathrm{n_1} = \mathrm{n_0}\frac{\mathrm{e}\varphi}{\mathrm{KTe}} \qquad (2\text{-}3)$$

The continuity equation also is:

$$\frac{\partial \mathrm{n_e}}{\partial \mathrm{t}} + \nabla.(n_e v_e) = 0 \qquad (2\text{-}4)$$

But we knew:

$$\nabla n_0 = v_0 = E_0 = 0$$
$$\frac{\partial n_0}{\partial t} = \frac{\partial v_0}{\partial t} = \frac{\partial E_0}{\partial t} = 0$$

In the continuity equation we can write:

$$\frac{\partial n_1}{\partial t} + \nabla \cdot (n_0 v_1 + n_1 v_1) = 0 \qquad (2\text{-}5)$$

With replacing approximation of $\nabla \cdot (n_1 v_1)$ we can write:

$$\frac{\partial n1}{\partial t} + \nabla \cdot (n_0 v_1) = 0$$

and because $\nabla = ik\hat{x}$ *and* $\frac{\partial}{\partial \mathrm{t}} = -i\omega$

we reach

$$-i\omega n_1 = -n_0 ikv_1 \qquad (2\text{-}6)$$

Now refer to the equations (2.6) and (2.3), we can write MHD approximation as:

$$-i\omega M n_0 v_{1i} = \frac{\left(en_0 ik\frac{KT_e}{M} + \gamma_i \mathrm{KT_i} ik\right) n_0 ikv_{i1}}{i\omega} \qquad (2\text{-}7)$$

So we reach to:

$$\omega^2 = k^2 \left(\frac{KT_e}{M} + \frac{\gamma_i KT_i}{M}\right) \quad (2\text{-}8)$$

with the limitation of $T_i \rightarrow 0$

we can write:

$$\omega^2 = k^2 (\frac{KT_e}{M})^{1/2} \quad (2\text{-}9)$$

Now for the bottom side and up side of the ionosphere values with taking on account the Fig. 3. we have:

T (90 km) = 300 k° and T(120 km) = 600 k° and

$K = 1\ .37 \times 10^{-23}$ and M(o)= 2.65×10^{-26} kg

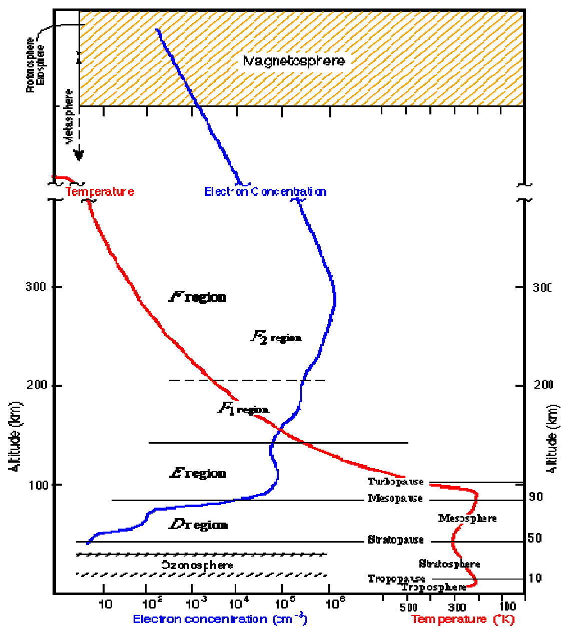

Fig. 3. Temperature and electron density in ionospher [4]

so:

At 90 kilometer from the earth surface:

$$\frac{\omega}{K}(O) = \left(\frac{KT_e(90\ km)}{M}\right)^{1/2} = \left(\frac{1.37\times10^{-23}\times300}{2.65\times10^{-26}}\right)^{1/2} = 3.93 \times 10^2 \quad (\frac{j}{kg})^{1/2} \quad (2\text{-}10)$$

And at the 120 kilometer from the earth surface:

$$\frac{\omega}{K}(0) = \left(\frac{KT_e(120\ km)}{M}\right)^{1/2} = \left(\frac{1.37\times10^{-23}\times600}{2.65\times10^{-26}}\right)^{1/2} = 5.56\times\ 10^2 \quad (\frac{j}{kg})^{1/2} \tag{2-11}$$

With Maxwell equation in the following: [5]

$$\nabla\times B = \mu_0(\dot{J}_f + \dot{J}_p + \varepsilon_0\dot{E}) \tag{2-12}$$

And rewriting this equation in the following form:

$$\nabla\times B = \mu_0(J_r + \varepsilon\dot{E}) \tag{2-13}$$

And putting:

$$\varepsilon = \varepsilon_0 + \frac{j_P}{\dot{E}} \tag{2-14}$$

and the following values:

$$\dot{J}_P = ne(V_{ip} - V_{ep}) \tag{2-15}$$

$$v_p = \mp\frac{1}{\omega cB}\frac{dE}{dt} \tag{2-16}$$

So:

$$\dot{J}_P = ne\left(V_{ip} - V_{ep}\right) = \frac{ne}{eB^2}(M+m)\frac{dE}{dt} = \frac{\rho}{B^2}\frac{dE}{dt} \tag{2-17}$$

Which from equation (2.14) it is obvious that :

$$\frac{\varepsilon}{\varepsilon_0} = 1 + \frac{\mu_0\rho C^2}{B^2} \tag{2-18}$$

With the approximate values about 2^{nd} >>1 we reach:

$$\frac{\varepsilon}{\varepsilon_0} \cong \frac{\mu_0\rho C^2}{B^2} \tag{2-19}$$

And

$$n = \sqrt{k} = \frac{\sqrt{\varepsilon}}{\sqrt{\varepsilon_0}} = \left(\frac{\mu.\rho C^2}{B^2}\right)^{1/2} \tag{2-20}$$

From the following (Fig. 4). We know the density of oxygen:

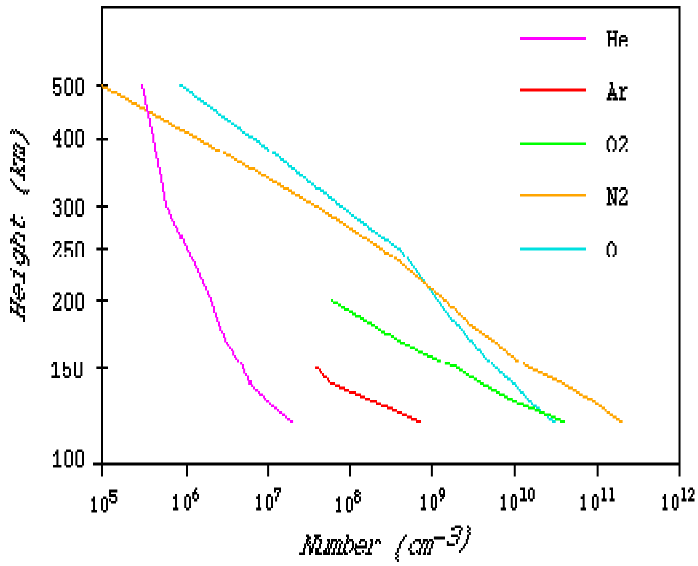

Fig. 4. Density of elements in ionosphere [6]

At 90 kilometer from the earth surface:

$$\rho(O) \propto 10^{13}(cm^{-3})$$

And at the 120 kilometer altitude:

$$\rho(O) \propto 10^{12}(cm^{-3})$$

Also we knew that the magnetic field intensity in E layer plasma about 1(Oe)[7]. We reach to:

$$B = \mu_0 H = 4\pi \times 10^{-7} \times \frac{1}{4\pi} \times 10^3 = 10^{-4} \ (T) \quad (2\text{-}21)$$

Then:

At 90 kilometer altitude:

$$n(O) = \left(\frac{4\pi\times10^{-7}\times9\times10^{16}\times5.3\times10^{-26}\times10^{19}}{10^{-8}}\right)^{1/2} = 1.73 \times 10^{6} \quad (2\text{-}22)$$

And about the 120 kilometer altitude:

$$n(O) = \left(\frac{4\pi\times10^{-7}\times9\times10^{16}\times5.3\times10^{-26}\times10^{18}}{10^{-8}}\right)^{1/2} = 5.47 \times 10^{5} \quad (2\text{-}23)$$

With regards to the speed of light c/n

At 90 kilometer from the earth surface:

$$c/n = 1.73 \times 10^2 \quad \text{m/s} \tag{2-24}$$

And at 120 kilometer from the earth surface:

$$c/n = 0.54 \times 10^2 \quad \text{m/s} \tag{2-25}$$

refer to the following figure(Fig. 5.) and considering a volume of polarized plasma we reach to the electric field as:

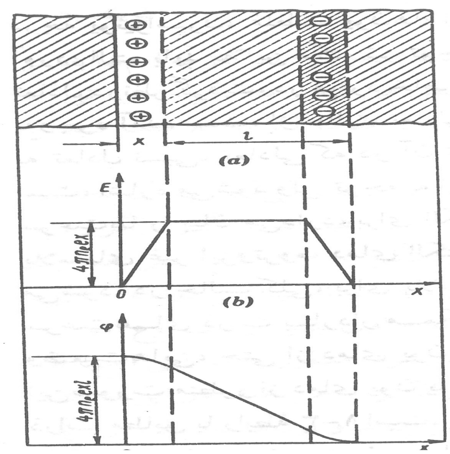

Fig. 5. Diagram of plasma state in the E layer [8]

$$E = 4\pi\sigma = 4\pi n_e e x \tag{2-26}$$

The electric potential is as:

$$\varphi = lE = 4\pi n_e e x l \tag{2-27}$$

That in this equation l is the width of E layer or 3×10^4 m.

If we put $x \approx l$:

$$E = e\varphi = 4\pi n_e e^2 l^2 \tag{2-28}$$

from Fig. 3 we know:

$$n_e(90km) = 10^4 \ (cm^{-3})$$
$$n_e(120km) = 10^5 \ (cm^{-3})$$

The energy will be:

$$E(90\ km) = 4\pi \times 10^{10} \times (1.6 \times 10^{-19})^2 \times (3 \times 10^4)^2 = 2.89 \times 10^{-18}\ j \tag{2-29}$$

$$E(120\ km) = 4\pi \times 10^{11} \times (1.6 \times 10^{-19})^2 \times\ (3 \times 10^4)^2 =\ 2.89 \times 10^{-17}\ j \quad (2\text{-}30)$$

Refer to $v = \sqrt{\frac{2E}{m}}$:
So:

1-At the bottom side of the E layer(90Km):

$$v(o) = \sqrt{\frac{2E}{m}} = 1.47 \times 10^4 \quad m/s \quad (2\text{-}31)$$

2-At the upper side of the E layer (120Km):

$$v(o) = \sqrt{\frac{2E}{m}} =\ 4.67 \times 10^4 \quad \frac{m}{s} \quad (2\text{-}32)$$

We know $\nu = \frac{E}{h}$

1-At:

$$\nu = \frac{2.89 \times 10^{-18}}{6.62 \times 10^{-34}} = 4.36 \times 10^{15} \quad \text{Hz} \quad (2\text{-}33)$$

2- At:

$$\nu = 4.36 \times 10^{16} \quad \text{Hz} \quad (2\text{-}34)$$

From equation (3.2) it showed that:

$$\cos\theta = \frac{1}{\beta.n(\lambda)}$$

And because:

$$V = \beta.c$$

We can write:

$$\text{Cos}(\theta) = \frac{c}{Vth.n(\lambda)} \quad (2\text{-}35)$$

It is resulted that the velocity of oxygen ion is greater than that of the of electromagnetic waves in E layer, obviously this is because the Cherenkov effect is possible.

So oxygen ion emits Cherenkov radiation in the following angles:
At 90 kilometer altitude:

$$\boldsymbol{\theta}(0) = 83.22^\circ \quad (2\text{-}36)$$

And at 120 kilometer altitude:

$$\boldsymbol{\theta}(0) = 89.327° \quad (2\text{-}37)$$

3. CONCLUSION REMARKS

1. It is shown that in two limit of height at E layer the thermal velocity of Oxygen ion is greater than the phase velocity of ionic wave of Oxygen and so Cherenkov radiation is possible.
2. At 90 kilometer altitude Cherenkov radiation emitted in $83.22°$ from oxygen ions.
3. At 120 kilometer from earth surface Cherenkov radiation emitted in $89.327°$from the same oxygen atoms.
4. The frequency of Cherenkov radiation is in UV range.
5. With increasing the height and temperature in E layer Cherenkov frequency increased.
6. In other hand increasing the height and temperature in E layer Cherenkov angle also increased.
7. Then with increasing the height and temperature in E layer the phase velocity of ionic waves increased.
8. With increasing the height and temperature in the E layer plasma would lead to increasing the thermal velocity of ions.

EXPERIMENTAL ACHIEVEMENTS

1. Cherenkov radiation is received by a magnetic satellite that circles around ionosphere and it is showed that Cherenkov frequency is in UV range [9].
2. In presence of electrical field in E layer refractive index is greater than 1, and Cherenkov radiation is observed [10].

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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