Coherent Transition Radiation Produced in Clouds, Ice and Salt by Shower Particles

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Abstract. Using the values of the dielectric constant, ε, determined with the help of various models the intensity of the coherent transition radiation (CTR) produced by extended air shower (EAS) particles is calculated in the meter wave length region. CTR produced at the inhomogeneities of Antarctic ice and mine salt dielectric constant is also considered. The possibilities of detection of such CTR and its influence on cosmic ray particle radio detection is discussed.

INTRODUCTION

Great number of experimental and theoretical works carried out after the predictions of G.A.Askarian [1] on the existence of negative charge excess in EAS and possible detection of coherent Cherenkov and transition radiation produced by this excess, show that the radio detection of very high energy particles can be applied for the investigation of cosmic ray particles and their interactions. In particular, the detection of decimetre wave length Cherenkov radiation produced by super high energy neutrinos in Antarctic ice after penetrating the Earth will open the neutrino astronomy (see the reports presented in the Proceedings of this Workshop). Nevertheless, despite the achievements and confirming results of accelerator experiments [2,3] there are many problems [4] to be solved before considering the radio method completely matured. It is necessary to take into account the contribution of other possible radiation production mechanism, especially, the contribution of coherent transition radiation (CTR). As an alternative mechanism to explain the additional radio signals observed during thunder weather [5] in the work [6] it has been shown that the CTR produced by the charge excess of high energy showers in clouds can be intense and give radio signal of the same amplitudes as the expected Cherenkov radiation. CTR can be produced also in parts of Antarctic ice where a variation of ε takes place, for instance, at the ice surface or in ice volume due to mixtures particles, mechanical inhomogeneities produced during the formation of ice. Such inhomogeneities in mine salt which is also sufficiently transparent to certain radio wave length interval also can be sources of CTR. These types of CTR can be detected by the antennas directly or after reflections.

The purpose of this short note is to turn attention to the consideration of the CTR production in air, ice and salt inhomogeneities of ε. The presented consideration and the estimates carried out using the calculated [6] and directly or indirectly measured (see [4] and this proceedings) values of ε show the necessity to make new investigation in this direction.

CTR due to Inhomogeneities in air ε (Clouds) by EAS

From the point of view of CTR one can describe the clouds and their properties as follows (see [6]): In dependence on the height upon the sea level there are four types of clouds: i)"Low" clouds which in their turn are divided in three types; "St", layered, which are at heights $H \simeq 0.4$ km and have mean thickness $D \simeq 0.4km$; "Sc", layered-cumulus, with $H \simeq 0.5 - 1$ km and $D \simeq 0.5$km and "Ns", layered-pluvious, with $H \simeq 1.5 - 2$km and $D \simeq 1$km; ii)"Middle" clouds, "Ae", high-cumulus and "As", high-layered. The both types have $H \simeq 3 - 4$km and $D \simeq 0.5$km.iii) "Upper" clouds,"Ci" or fleecy clouds with $H \simeq 6 - 8$km and $D \simeq 2$km, and iv) "Cu" or "clouds of vertical development " with $H \simeq 1.2 - 2$km and $D \simeq 0.5 - 5$km.

When the air temperature is $\geq -10^o$ C more than half of the clouds are partially drop-containing, while the clouds of low heights consist mainly of drops. The radius of these drops is from 2 up to 15 μm with mean radius $r_0 \simeq 5\mu$m. The density of the drops is $N_\nu = (1-6)10^8 m^{-3}$ with mean distance between the drops $l \simeq 3\mu$m. Considering the cloud as a strongly rarefied gas one can write

$$\varepsilon = 1 + \varepsilon_0 + \varepsilon_1, \tag{1}$$

where ε_0 and ε_1 are corrections to the vacuum due to air and water molecules, respectively. Having no experimentally measured values of ε for sufficiently long (meter) waves we have modeled [6] the cloud ε and obtained $\varepsilon_0 = 5 \cdot 10^{-4}$ and $\varepsilon_1 = 10^{-5}$.

As it is well known (see [7]) the EAS particles are in a pancake with disk radius $r_1 \simeq L/4$ and thickness $d \simeq L/32$ where $L = L_0 exp(H/H_0)$ and $L_0 = 310m$ are the air radiation length at heights H and sea altitude, respectively, $H_0 = 7.5km$. The number of the negative excess particles $N_\nu = N_e(N_e - N_{e^+})/(N_e + N_{e^+}) = \nu N_e$ with ν decreasing with the increase of excess electron energy, E_e and with radial distribution $\sigma_\nu(r) = N_\nu exp(-r/r_1)/2\pi r r_1$. For $E \sim 25$ MeV $\nu \sim 0.04$ [9]. Therefore, for EAS energy $E_0 \simeq 10^{17}$, $N_e \simeq 5.10^7$ and $N_\nu \simeq 2.10^6$. Note that N_e, and N_ν increase linearly with the increase of E_0. If EAS maximum takes place at the lower boundary of clouds then the effective energy of electrons is $E_{eff} \sim 25MeV$ and $\gamma_{eff} = E_{eff}/mc^2 \sim 50$.

In the meter wave region considering the clouds as a homogeneous medium, i.e neglecting the layered cloud structure resulting in the enhancing the CTR yield, with more or less sharp lower boundary, one can write the following approximate expression for TR intensity frequency distribution from single excess electron [6]

$$\frac{dW}{d\omega} \simeq \frac{\alpha\hbar}{\pi} F(\gamma, \varepsilon_o, \varepsilon_1) = \frac{\alpha\hbar}{\pi}\left[(1+\frac{2\varepsilon_0}{\varepsilon_1}) ln(1+\frac{\varepsilon_1}{\varepsilon_0-\gamma^{-2}}) - 2\right]. \qquad (2)$$

When $\varepsilon_0\gamma^2 \gg 1$ with an accuracy up to the terms $(\varepsilon_1/\varepsilon_0)^2$:

$$\frac{dW}{d\omega} \simeq \frac{\alpha\hbar}{6\pi}\left[\frac{\varepsilon_1}{\varepsilon_0}\right]^2, \qquad (3)$$

which is convenient for estimates when the electron energies are higher than 200 MeV and for media for which the radiation length is sufficiently short. In the case of clouds when $\gamma_{eff} \sim 50$ after integration (2) over frequency interval $\Delta\omega = 0.1\omega$ for wave length $\lambda = 50$m one obtains

$$W \simeq \frac{\alpha\hbar\omega}{\pi} F(\gamma, \varepsilon_0, \varepsilon_1)\Delta\omega = 7.1.10^{-29} J. \qquad (4)$$

Integrating the distribution $\sigma_\nu(r)$ for an antenna with diameter R one obtains $N_{\nu,eff} \simeq N_\nu(1-exp(-R/r_1))$, which for $E_0 = 10^{17}$ eV and R = 50 m gives $N_{\nu,eff} \simeq 9.5.10^5$. If the shower thickness at its maximum is less than the radiation length, then the excess electrons radiate coherently, and the radiation energy increases $N^2_{\nu,eff}$ times giving $W_{N_{\nu,eff}} \simeq 6.4.10^{-17}$ J. Taking the pancake thickness equal to 10 m and assuming the detector integration time equal to the time of the shower passage, we obtain the detected power $P \simeq 2.10^{-9}$ W, providing $\simeq 0.6mV$ signal.

CTR due to Inhomogeneities in Ice and Salt

A nice review of the physical properties of Antarctic ice from the point of view of particle radio detection technique is given in [4]. For the radio wave region in the average the ε values vary form 1 up to 3.18 when the depth from the surface increases. This is connected with the formation of glacial ice from upper snow through firn. However the temperature gradients, mechanical fluctuations, volcanic ash and other reasons can result in the formation of local and layer ε inhomogeneities with thicknesses from centimeters up to kilometers. Similar ε inhomogeneities are observed in mine salt according to the measurements of Japanese physicists (see this proceedings and [8]). Considering the ice or salt as inhomogeneous media with $\varepsilon(\omega, \vec{r}) = \varepsilon_0(\omega) + \Delta(\omega, \vec{r})$ one obtains the following formula for the single excess particle TR frequency spectrum for wave lengths much larger than the mean square sizes l of the inhomogeneities $\lambda \gg l$

$$\frac{dW}{d\omega} = \frac{3\alpha\hbar Dh(\omega)}{16\pi\varepsilon^{3/2}}\left[ln\frac{(\lambdabar/l)^2}{\mid 1-\beta^2\varepsilon_0 \mid} - 1\right]\frac{\lambdabar^2}{l^2}, \qquad (5)$$

where $h(\omega) = (\omega^4/18\pi c^4) \int \Delta(\omega, \vec{r_1})\Delta(\omega, \vec{r_2}) dV_{\vec{r_1}-\vec{r_2}}$ is the extinction coefficient, D is the thickness on which CTR is produced, i.e. the length when the shower charge excess is large (see the curves of Figs.1 of [2,10]) and $\lambda\!\!\!^{-} = \lambda/2\pi$.

Unfortunately, it is impossible to make estimates using (5) because there are no data on $\Delta(r, \omega)$ and l, and experimental investigations for their determination are desirable. Nevertheless, the results obtained for foam and other inhomogeneous media shows that TR intensity is higher than that from single interface which in its turn is higher then the Cherenkov radiation from showers (see [2,10]). Therefore, one can not neglect the radiation given by (5), and additional theoretical as well as experimental studies are necessary.

Discussion

As it follows from the above discussion the CTR production mechanism in clouds, ice and salt is similar to that of x-ray TR. In both cases the differences between ε of the two neighboring media is small, while in case of clouds the εs themselves are very close to unity. For relativistic particles in all cases the emission angles are small, $\theta \sim 1/\gamma$. This later fact makes more difficult (easier) the detection and measurement of the above discussed CTR of the showers produced by high energy cosmic ray (accelerator) particles since detectors with larger (smaller) acceptance are necessary.

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