Transition radiation as a tool for radio detection of ultra high energy neutrinos

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High energy neutrinos passing through the Antarctic ice and lunar regolith can produce radio pulses. A good number of experimental groups have been continuing investigations on these radio pulses. Along with VHF -UHF radio pulses, VLF-LF-MF radio pulses are also emitted from the Antarctic ice-air interface and lunar regolith–vacuum interface due to excess negative charge of the extensive ice shower (EIS) and lunar regolith shower (LRS) produced by neutrinos. In this paper, some important aspects of VLF-LF-MF radio emission (RE) from EIS and LRS in the ultra high energy (UHE) range have been studied theoretically on the basis of the transition radiation (TR) mechanism. A moon-based experimental set up for receiving lunar radio pulses and then transmitting the same to earth-based or lunar orbital satellite borne radio telescope has also been proposed. Simultaneous investigation of VHF-UHF and VLF-LF-MF RE could give more confirmed information of the original event characteristics. RE model in the framework of TR for EIS & LRS exhibits significant characteristics with respect to frequency, shower size and zenith angle variation and hence, TR mechanism can be utilized as a tool for radio detection of UHE particles in the VLF-LF-MF band. On-going projects of EIS & LRS may incorporate radio channels for <10 MHz to widen the scope of radio detection of UHE particles.

Keywords: Radio pulses, Radio emission, Transition radiation mechanism, Ultra high energy neutrinos, Extensive ice shower, Lunar regolith shower

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1 Introduction

It has been known nearly 100 years now that the earth is continuously bombarded with various types of highly energetic particles from space. The discovery of these particles is attributed to Victor Hess (1912). He established the extra-terrestrial origin of the new particles by measuring a higher particle flux when performing a detection experiment in a balloon at high altitude. In the early days of studies of these particles (christened as cosmic rays (CR) by Millikan in the year 1926), the first particles to be detected were gamma ray photons. Subsequently, it has been found that cosmic rays are particles coming from outer space, such as protons, $\alpha$-particles, heavier nuclei, etc. Small quantities of anti-particles, electrons and muons are also present. In addition to these charged particles, there are $\gamma$-photons and the weakly interacting neutrinos. The neutrinos are usually treated separately from the other particles due to their very different characteristics in terms of interaction length. Some of these particles are of extremely high energy (EHE) ($\sim 10^{18}$ eV) or ultra high energy (UHE) ($>10^{19}$ eV).

Recent studies make compelling arguments that input from neutrino observations will be necessary to resolve the ultra high energy cosmic ray (UHECR) problem$^1$ regarding CR origin. The study of physics or astrophysics of UHECR is intimately linked with the emerging field of neutrino astronomy and it has opened a new branch under the name Ultra High Energy Neutrino Astronomy. The detection of UHE neutrinos will open a new window to understand the farthest and most energetic phenomena in the universe.

It is to be mentioned that detection of radio emission (RE) from extensive air showers (EAS) initiated by CRs (of primary energy $E_p \sim 10^{16}$ eV) by Jelley et al.$^2$ in 1965 opened a new era of cosmic ray studies, with most interest centering on the radio detection of high energy particles. Theoretical as well as experimental aspects of the whole spectrum of the radiation from ~50 kHz to ~550 MHz (for mean energy $10^{16}$ eV) have been studied extensively by different groups all over the globe$^{3,4}$ in a period of almost five decades since 1965. Production mechanism for RE from EAS is now well established to be geo-synchrotron radiation in the
frequency band \(>10\, \text{MHz}\) (ref. 5) and transition radiation (TR) for \(<10\, \text{MHz}\) (ref. 6). From the last quarter of the 20th century, some laboratories are being engaged in detection and investigation of giant air showers (GAS) with \(E_p>10^{19}\, \text{eV}\).

Theoretical as well as experimental advances gained in the field of RE studies over the pretty long period of almost five decades and the necessity of detection of high energy cosmic neutrinos have given birth to UHE neutrino astronomy based on radio methods. It is worth mentioning that theoretical prediction by Askarayan\(^7,8\) of negative charge excess in electron-photon cascade produced by a HE particle in a dense medium forms the base of radio astronomical method (RAM) of neutrino detection. Coherent emission from this net negative charge gives rise to coherent Cherenkov radiation (RCR) at HF-VHF band of radio frequency. Experimental confirmation of Askarayan effect\(^9,10\) in 2000 concretizes the base of the RAM.

Neutrinos have several advantages over cosmic rays as sources of astronomical information. Being electrically neutral, they point back to their sources, whereas all but the highest energy (\(E_p\sim10^{20}\, \text{eV}\)) cosmic rays are bent in intergalactic magnetic fields. Since they only interact weakly, neutrinos do not suffer from Greisen-Zatsepin-Kuzmin (GZK) attenuation or attenuation at their sources like cosmic ray protons. And at the highest energies, neutrinos actually have very high cross sections for interaction.

To study the highest energy neutrinos is extremely difficult because of their very low fluxes. To resolve this problem, larger detectors of huge effective volume with higher duty cycles and multiple detection techniques are needed. In recent years, several detection methods and techniques are being employed and/or studied. Among them, the radio technique is one of the most promising alternatives for neutrino detection at UHE. Due to their excellent radio frequency wave propagation properties, Antarctic ice and lunar regolith are being considered as huge detector media where antennas can be placed to monitor the potential radio signals.

The radio signals emitted by lunar regolith showers initiated by UHE particles can be detected by Earth based radio telescopes also. The expected sensitivity for observation of such events at the Giant Meterwave Radio Telescope (GMRT) both for UHE CR and UHE neutrino interactions are presented by Panda \textit{et al.}\(^11\). Their finding is that for 30 days of observation time, a significant number of detectable events may be expected above \(10^{20}\, \text{eV}\).

This paper presents the feasibility of utilizing the TR produced by UHE neutrinos in different dielectric media interfaces, viz. Antarctic ice-air and lunar regolith-vacuum, as a tool for radio detection of UHE particles. Experiments, conceptual in nature, are also presented with an aim to invite attention of sophisticated laboratories for testing the degree of resonance between the model developed in the present work and the experiments going on in various labs all over the globe, viz. Lunar Orbital Radio Detector (LORD)\(^12\), ANtarctic Impulse Transient Antenna (ANITA)\(^13\), ICECUBE\(^14\), Fast On-orbit Recording of Transient Event (FORTE)\(^15\), AUGER (Pierre Auger Collaboration)\(^16\), etc.

2 Theory
The phenomenon of transition radiation, discovered theoretically by Ginzburg & Frank\(^17\), occurs when a charged particle passes through a boundary between two dielectrically different media. This radiation is known as transition radiation.

2.1 TR Model for Antarctic ice
High energy neutrinos passing through the earth generate electromagnetic showers in the Antarctic ice called extensive ice shower (EIS) (ref 18). When charged particles of the EIS cross the surface of separation of ice and air, the phenomenon of TR must occur. For the VLF-LF-MF band, all the charged particles of the shower may be assumed, for mathematical convenience, to be concentrated at a point instead of distribution over a region and only the excess negative charge, in effect, will contribute to the TR. For a particle of charge, \(e\), moving with relativistic velocity, \(v\), along the \(z\) axis and crossing the boundary plane ice-air at \(z=0, t=0\), the wave equation for TR is given by\(^19\):

\[
\left(\frac{d^2}{dz^2} + \lambda_{iz}^2\right)(\vec{E}_{\omega}, \vec{H}_{\omega}) = 0 \quad \ldots (1)
\]

Solving this equation, the radiation field (electric) in the forward direction is obtained as:

\[
\vec{E}' = \vec{E}_{iz} e^{i\lambda_{iz}z} \quad \ldots (2)
\]

For a vertical EIS, the magnitude of the horizontal component of the field is

\[
\vec{E}_{iH} = \frac{\varepsilon N e \lambda_{iz} \eta_{iz} k}{2\pi^2 v^2 \xi^2 \cos \theta} \quad \ldots (3)
\]

and the vertical component of the field is:
\[ \vec{E}_{IV} = \frac{\varepsilon Ne_\eta_\lambda_k^2}{2\pi^2v_\zeta^2}\cos^2 \theta \] 

... (4)

where,

\[ N = \text{total number of shower particles at ice-air interface}; \]

\[ \varepsilon Ne = \text{excess negative charge}; \]

\[ e = \text{electronic charge}; \]

\[ k = \omega / c = 2\pi f / c = \text{wave number}; \]

\[ \lambda_i^2 = \frac{\omega^2}{c^2} \chi_i - k^2; \] where \( \chi_i = \varepsilon_i\mu_i; \)

\[ \lambda_a^2 = \frac{\omega^2}{c^2} \chi_a - k^2; \] where \( \chi_a = \varepsilon_a\mu_a; \)

\[ \varepsilon_a, \varepsilon_i \text{ are dielectric constants; and } \mu_a, \mu_i \text{ are permeabilities of air and ice, respectively}; \]

\[ \eta_\sigma = \left( \varepsilon_v / \varepsilon_a \right) / (k^2 - \omega^2 / c^2 \chi_i); \]

\[ + (-1 + \varepsilon_v / \varepsilon_a) / (k^2 - \omega^2 / c^2 \chi_a); \]

\[ \zeta = \lambda_a\varepsilon_i + \lambda_i\varepsilon_a; \]

\[ \tan \theta = Z/R; \]

\[ Z = \text{height of the antenna from the ice-air interface}; \]

\[ R = \text{distance of the antenna from the shower axis}. \]

### 2.2 TR model for lunar regolith

The lunar surface might be an extremely good target for the radio emission of neutrinos with energies of \( >10^{20} \) eV. When charged particles of the LRS cross the surface of separation of lunar regolith and vacuum, the phenomenon of TR must occur. For the VLF-LF-MF band, all the charged particles of the shower may be assumed, for mathematical convenience, to be concentrated at a point instead of distribution over a region and only the excess negative charge, in effect, will contribute to the TR. For a particle of charge \( e \) moving with relativistic velocity \( v \) along the \( z \) axis and crossing the boundary plane LR-vacuum at \( z=0, t=0 \), the wave equation for TR is given by \[^19]\):

\[ \left( \frac{d^2}{dz^2} + \lambda_{i,v}^2 \right) (\vec{E}_{ao}, \vec{H}_{ao}) = 0 \] 

... (5)

Solving this equation, the radiation field (electric) in the forward direction is obtained as:

\[ \vec{E}_{IV} = \vec{e}_0 e^{i\chi z} \] 

... (6)

For a vertical LRS, the magnitude of the horizontal component of the field is:

\[ \vec{E}_{IV} = \frac{\varepsilon Ne\lambda_v \eta_v k}{2\pi^2v_\zeta^2}\cos \theta \] 

... (7)

and the vertical component of the field is:

\[ \vec{E}_{IV} = \frac{\varepsilon Ne \eta_v k^2}{2\pi^2v_\zeta^2}\cos^2 \theta \] 

... (8)

where,

\[ N = \text{total number of shower particles at lunar regolith-vacuum interface}; \]

\[ \varepsilon Ne = \text{excess negative charge}; \]

\[ e = \text{electronic charge}; \]

\[ k = \omega / c = 2\pi f / c = \text{wave number}; \]

\[ \lambda_v^2 = \frac{\omega^2}{c^2} \chi_v - k^2; \] where \( \chi_v = \varepsilon_v\mu_v; \)

\[ \varepsilon_v, \varepsilon_i \text{ are dielectric constants and } \mu_v, \mu_i \text{ are permeabilities of vacuum and lunar regolith, respectively}; \]

\[ \eta_v = \left( \varepsilon_v / \varepsilon_a \right) / (k^2 - \omega^2 / c^2 \chi_v); \]

\[ + (-1 + \varepsilon_v / \varepsilon_a) / (k^2 - \omega^2 / c^2 \chi_v); \]

\[ \zeta = \lambda_v\varepsilon_i + \lambda_i\varepsilon_v; \]

\[ \tan \theta = Z/R; \]

\[ Z = \text{height of the antenna from the LR-vacuum interface}; \]

\[ R = \text{distance of the antenna from the shower axis}. \]

### 3 Results

#### 3.1 RE characteristics for extensive ice shower (EIS)

##### 3.1.1 Shower size vs Field strength

Figure 1 shows the field strength (which is electric field intensity divided by bandwidth of the radio detector) obtained from Eqs (3) and (4) for horizontal and vertical components, respectively, as a function of different shower size for vertical showers. The field strength rises linearly with the shower size.

##### 3.1.2 Frequency spectrum

Figure 2 shows the frequency spectrum (variation of field strength with frequency) obtained from
Eq. (4). This spectrum is found to be a decreasing function of frequency whereas RCR (Askaryan effect) frequency spectrum\(^{20}\) is an increasing function of frequency.

3.1.3 Depth vs negative charge excess

Figure 3 shows the depth (depth of the ice-air interface with respect to the position of first interaction of the incoming neutrino) vs negative charge excess plot in ice obtained from model developed by Muniz & Zas\(^{21}\).

3.1.4 Angular distribution of intensity of TR in the forward direction for ice-air interface

The total energy radiated into a solid angle d\(\Omega\) in the forward direction is given by:

\[
\frac{d\phi}{d\Omega} = \frac{e^2 v^2 \cos^2 \theta \cos^2 \theta \left| (1 - v^2/c^2) / (1 - v/c) \sqrt{E - v^2/c^2} - (E - v^2/c^2) \sqrt{E - v^2/c^2} \right|^2}{\pi e^3 \left[ 1 - (v^2/c^2) \cos^2 \theta \right] [1 - (v/c)^2] (E - v^2/c^2) (E \cos \theta + \sqrt{E - v^2/c^2})} 
\]

... (9)

Angular distribution of the intensity of TR for ice-air interface is calculated with \(\varepsilon = 2.9\) for ice and shown in Fig. 4. The pattern is found to be directional in nature.

3.1.5 Inclined EIS

From the available experimental data of Gauhati University Cosmic Ray (GUCR) Research Laboratory...
at 120 kHz (ref. 22) for inclined showers, variation of field strength with zenith angle has been studied. For a neutrino initiated lunar regolith shower having zenith angle \( \phi \), the magnitude of the vertical component of the TR field is obtained by modifying the expressions formulated for EAS. For this, relations between \( E_p \) and \( N \) given by Matthews\(^{23} \) are adopted. Results are shown in Fig. 5.

3.2 Radio emission (RE) characteristics for lunar regolith shower (LRS)

3.2.1 Shower size vs Field strength

Figure 6 shows the field strength obtained from Eqs (7) and (8) as a function of different shower size for vertical showers. The field strength rises linearly with the shower size.

3.2.2 Frequency spectrum

Figure 7 shows the frequency spectrum obtained from Eq. (8). The spectrum also has a decreasing trend with increase in frequency whereas for RCR from LRS, the spectrum has an increasing trend with increase in frequency\(^{24} \).

3.2.3 Depth vs negative charge excess

The depth vs negative charge excess graph (Fig. 8) is obtained from the model developed by Saltzberg et al.\(^9 \)

3.2.4 Angular distribution of intensity of TR in the forward direction for lunar regolith-vacuum interface

Angular distribution of the intensity of TR for lunar regolith-vacuum interface is calculated using Eq. (9) with \( \varepsilon = 3 \) for lunar regolith and shown in Fig. 9. The pattern is found to be directional in nature. Figure 9 is found to be almost similar to Fig. 4, the only difference being absence of small side lobe in Fig. 9.

3.2.5 Inclined LRS

Adopting the same procedure as in inclined EIS, variation of field strength with zenith angle for different sizes of LRS are obtained and shown in Fig. 10.

3.3 Experimental techniques

On the basis of the important characteristics of RE obtained for Antarctic ice and lunar regolith, experimental techniques, for utilizing these characteristics in gathering information of the UHE particles, are conceptualized and presented.

3.3.1 For Ice

Studies suggest that Antarctica is electromagnetically extremely quiet. From the model developed, it is found that VLF-LF-MF field strengths from EIS is a function of charge excess, shower size/primary energy and distance from the shower axis. Higher field strengths are expected to be observed in the VLF-LF-MF band of frequencies (Fig. 2). On the basis of this, a method for neutrino detection is proposed as:

(i) An array of VLF-LF-MF loop antenna is to be installed on Antarctic ice surface above the VHF-UHF antenna of Radio Ice Cherenkov Experiment (RICE) project\(^{25} \).
(ii) Coincidences are to be taken between the VLF-LF-MF and VHF-UHF emission and the field strengths of both are to be determined using Eqs (3) and (4) for vertical showers and using corresponding equation for inclined showers\(^6\) for VLF-LF-MF band and using RCR model\(^{21}\) for VHF-UHF band.

(iii) With the observed field strengths for VLF-LF-MF RE, \(\varepsilon\), \(N\) and shower axis coordinates, \(X_0\), \(Y_0\) are to be determined adopting Artificial Neural Network (ANN).

(iv) Knowing \(\varepsilon\) and \(N\), depth of first interaction can be estimated from graphs similar to Fig. 3 for different \(E_p\).

(v) Step iii and iv are to be followed for field strengths for VHF-UHF antenna buried in ice.

Parameters \(\varepsilon\), \(N\), \(X_0\), \(Y_0\) and depth of first interaction obtained from VLF-LF-MF measurements are to be compared with those obtained from VHF-UHF measurements for each event to arrive at some concrete conclusions.

3.3.2 For Lunar regolith

Measuring field strengths at least at five different positions using Eqs (7) and (8) for vertical showers and using corresponding equation for inclined showers\(^6\) for VLF-LF-MF band and using RCR model\(^{21}\) for VHF-UHF band, parameters \(\varepsilon\), \(N\), shower axis coordinates and \(\varphi\) can be estimated by adopting ANN. Knowing \(\varepsilon\) and \(N\), depth of first interaction can be estimated from graphs similar to Fig. 8 and for different neutrino energies, from which interaction characteristics of neutrinos in lunar regolith can be obtained. Like EIS, in this case also, \(\varepsilon\), \(N\), \(X_0\), \(Y_0\) estimated from VLF-LF-MF measurements can be compared with those obtained
from VHF-UHF measurements to arrive at some concrete conclusions.

It is worth mentioning that radio detection by RAM with earth based detectors are interrupted by atmospheric noises including noise pulses from EAS RE, whereas radio detection by moon based detectors is free from all these noises. However, conducting simultaneous observations using several well separated earth based antennas in an array would sharply reduce the number of false events due to local interference.

3.3.3 Proposed experimental set up

An experimental set up has been proposed here which could detect VLF-LF-MF pulses induced by neutrinos interacting with the lunar regolith, up convert the pulses to VHF range and then transmit the VHF pulses to the lunar orbital satellite borne or earth based radio telescopes. Block diagram of the proposed experimental set up is shown in Fig. 11.

VLF-LF-MF radio pulses coming from the LR-vacuum interface can be received by a loop antenna placed on the lunar surface. Then the pulses can be fed to the matching unit and to the transponder. Here, the received signal is converted to the VHF signal and fed to the helical antenna for transmission. The signal may be transmitted either to the lunar orbital satellite based or earth based radio antenna. Block diagram of the transponder is given in Fig. 12.

The transponder converts a signal of VLF-LF-MF to VHF-UHF. Some up-converters, IF amplifiers, RF band pass filters and high power amplifiers are necessary for the transponder to convert the VLF-LF-MF signal to the VHF-UHF signal. Thus, the concept developed leads to some possibility for VHF-UHF pulses, due to RCR mechanism, recorded by the earth based detector to be correlated with VLF-LF-MF pulses, due to TR mechanism, recorded by moon based detectors.

4 Discussions

An analysis of RE from showers initiated by UHE particles impinging different dielectrics, viz. Antarctic ice and lunar regolith are carried out in the scheme of TR. Several important characteristics for these two different situations have emerged as the outcome of the analysis.

4.1 For Ice

EIS is found to have one important and effective characteristic, i.e. variation of charge excess with depth (Fig. 3). In this context, it needs to be mentioned that high level projects, viz. Radio Ice Cherenkov Experiment (RICE), ANITA, ICECUBE, AUGER, etc. are going on for frequency range 100-1000 MHz. It is seen from the
model developed that VLF-LF-MF field strengths from EIS is a function of negative charge excess, neutrino energy and shower axis coordinates and higher field strengths may be observed at this band of frequencies. Hence, if an array of VLF-LF-MF antenna is installed on Antarctic ice surface above the VHF-UHF antenna of RICE project and field strengths of each of these antenna systems are measured taking coincidences between VLF-LF-MF antenna system and the VHF-UHF antenna system, then $\varphi$, $\varepsilon$, $N$ and shower axis coordinates can be calculated for each neutrino event from the VLF-LF-MF field strengths utilizing the theory developed in the present work. Such values can be calculated for VHF-UHF channel also for the same neutrino events from Radio Cherenkov Radiation model (RCR). Knowing $\varepsilon$ and $N$, depth of first interaction can be estimated from graphs similar to Fig. 3 and for different neutrino energies. Thus, an investigation on the correlation between depth of first interaction and neutrino energy will give a picture of behaviour of neutrinos in ice.

Following points are of considerable importance in the implementation of the proposed method:

(i) Communication signals in the Antarctic are known to be in the HF-VHF band. As such, there is not any possibility of interference with the proposed VLF-LF-MF antenna placed on ice surface.

(ii) VLF-LF-MF antenna register pulses due to TR mechanism only because RCR for this band is negligible. Moreover, for TR mechanism, question of absorption of radiation in ice does not arise.

(iii) By simultaneous observation of VLF-LF-MF and VHF-UHF radiation associated with the same events, it is possible to estimate different parameters of the events from two independent observations, importance lying on the fact that the production mechanism of pulses for the two bands are different.

(iv) RE from EAS seems to appear as a significant background for EIS observation. However, since coincidences are taken between VLF-LF-MF and VHF-UHF antennas and also different parameters of the EIS obtained from these two independent observations are compared, it is possible to reject noise pulses.

4.2 For Lunar regolith

Characteristics similar to EIS are obtained for LRS also. If an array of VLF-LF-MF antenna is installed on the lunar surface and field strengths are measured, then parameters $\varphi$, $\varepsilon$, $N$, $X_0$, $Y_0$ can be estimated adopting ANN. Knowing $N$ and $\varepsilon$, depth of first interaction can be estimated from graphs similar to Fig. 8 and for different neutrino energies, from which interaction characteristics of neutrino in lunar regolith can be obtained. It is worth mentioning that radio detection by RAM with earth based detectors is interrupted by atmospheric noises including noise pulses from EAS RE, whereas radio detection by moon based detectors is free from all these noises due to absence of atmosphere in the moon's environment.

From Fig. 7 and the works of Gorham et al., it is seen that, TR VHF-UHF field strength $\ll$ TR LF field strength and RCR LF-MF $\ll$ TR VLF-LF-MF field strength. Hence, lunar orbital satellite borne VHF-UHF antennas can be expected to register only RCR pulses and VLF-LF-MF antennas can be expected to register TR pulses only. Thus, correlation studies of these pulses at VLF-LF-MF and VHF-UHF will provide additional confirmation on the mechanisms. If delays are introduced in the radio channel of Fig. 11 and if pulses are received in the
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