Chapter 1

Introduction

1.1 Ultra high energy (UHE) messengers from outer space:

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' 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 of 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).
1.2 The GZK cutoff

Ultra High Energy Cosmic Rays (UHECR) are more mysterious under the GZK mechanism [1][2], which may lead to the GZK cutoff in the spectrum. UHE cosmic rays beyond the cutoff energy can interact effectively with the 2.7K microwave background radiation (MBR) via

$$\gamma_{2.7} + p \rightarrow \Delta^+ \rightarrow p + \pi^0 \text{ or } n + \pi^+$$ (1.1)

which implies that they cannot survive more than \(~50\) Mpc in intergalactic space. According to the GZK [1][2] bound, the UHECR produced in any known extra galactic source should have an exponential cut-off at energies \(E \sim 5 \times 10^{19}\) eV. On the other hand, the number of observed cosmic ray events beyond the cut-off is growing and leads to a paradox within standard frameworks of cosmological and particle physics models. About twenty events at \(~10^{20}\) eV have been observed by five different experiments [3]. The number of recorded events is already big enough to convince that the cosmic ray energy spectrum extends well beyond the theoretically expected GZK cutoff.

The detection of UHECRs of energies above \(10^{19}\) eV, specially super-GZK (Greisen-Zatsepin-Kuzmin) events, entails various unsolved puzzles and accordingly brings us serious challenges of understanding UHECRs: their origins, compositions, unusual largeness of energy, distribution of arrival directions and times, interactions with background particles or fields, interactions with the atmosphere and showers generated thereof, and detection methods.

1.3 Models of UHE cosmic ray origin

The problem of origin of cosmic rays with energies beyond \(10^{15}\) eV is still not fully solved. The astrophysical process of CR origin up to the knee are basically understood. The sources are Galactic Super Nova Remnants (SNR)[4]. After decades of attempts

\(^{1}1\text{Mpc}=3.1 \times 10^{24}\text{cm}\)}
to discover the origin of UHECRs, present results are still inconclusive. Cosmic rays of energy above $5 \times 10^{19}$ eV are almost certain to be of extragalactic origin. Various models of UHE cosmic ray origin have been proposed. Models can be categorized into two classes: bottom-up models in which particles are accelerated from a lower energy, and top-down models in which particles decay from a higher energy.

1.3.1 Bottom-up Models:

In bottom-up models, particles are accelerated to ultrahigh energies within extreme astrophysical environments, such as cluster shocks, active galactic nuclei (AGN), neutron stars, and maybe some environment associated with gamma-ray bursts (GRBs). Usually these extreme environments are very dense. How ultrahigh-energy particles escape from these dense regions without losing much energy through the scattering with particles therein is a serious intrinsic problem.

In addition, most of particles under the GZK mechanism cannot maintain energies beyond the GZK threshold (around $10^{20}$ eV) after traveling a distance longer than about 50 Mpc, so that it is unlikely for UHECR sources to be located outside the GZK zone, a region with a radius of about 50 Mpc around the earth. Unfortunately, there are very few powerful enough sources detected till date within the GZK zone. These few sources can hardly explain UHECR data, in particular, the spectrum and the distribution of arrival directions.

1.3.2 Top-down Models:

In top-down models, UHECRs are produced via decays of very massive particles (or topological defects) that may be relics of the early universe. These very massive relic particles might behave like dark matter and reside in the local dark halo, waiting for decays that generate UHECRs reaching us. These very massive particles are exotic, i.e., they are beyond the standard model of particle physics. Their unconfirmed existence is
1.4 Cosmic Neutrinos

Cosmic neutrinos originate from outer space in contrast to neutrinos produced in cosmic-ray interactions with atmospheric nuclei. Neutrinos are known to emanate from nuclear processes in the Sun, from Supernova explosions, and from interactions of cosmic rays with atmospheric molecules. All these processes essentially generate neutrinos of energy below 1 GeV. For the UHE cosmic neutrinos, one specific production mechanism is related to the GZK cutoff. Within a short time after formation, the charged pions produced in the GZK reaction (Eqn1.1) decay into secondary leptons and neutrinos through

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \]  

Provided the GZK mechanism is properly understood, this source can be considered as a standard candle of UHE neutrinos.

Cosmic neutrinos can interact with nucleons or electrons in the atmosphere and in any dense media viz Antarctic ice, lunar regolith etc. The interaction (\(\nu N\)) or (\(\nu e^-\)) is the weak interaction (WI) mediated by the \(W^\pm\) or \(Z^0\) boson; hence, it is categorized as a Charged Current (CC) or a Neutral Current (NC) interaction if mediated by the \(W^\pm\) or \(Z^0\) bosons, respectively.

A neutrino can interact only through the W- and Z-boson mediated channels of the electroweak interaction, and the very low likelihood for a neutrino to interact with a nucleon suggests that the interaction probability will be nearly equal for all target

an essential problem in this kind of models.

In addition, many top-down models involve QCD (Quantum Chromo Dynamics) fragmentation in the production of UHECRs. UHECRs originating from such fragmentation are mostly photons and neutrinos, which seem to be disfavored by present data. However, whether photons or neutrinos can be UHECR primaries is still not concluded.
nucleons in the nucleus. This means that the surface sensitivity should be removed, and the resulting interaction length for a neutrino in the material becomes

\[ L_{int}^\nu = \frac{1}{\sigma_{\nu p} N_A \rho} \]  (1.3)

where \( L_{int}^\nu \) is the average interaction length for a neutron traversing a material composed of nuclei with \( A \) nucleons each, \( \sigma_{\nu p} \) is the neutron-nucleus cross section, \( \rho \) is the mass density and \( N_A \) is the Avogadro number.

The total cross section for neutrino-nucleon interactions above \( E_\nu = 10^{15} \text{ eV} \) is composed of two parts, one for the neutral current (NC) interactions (\( \nu + N \to \nu + \text{anything} \)) and one for the charged current (CC) interactions (\( \nu + N \to l^- + \text{anything} \)). These cross sections can be parametrized[6] as

\[ \sigma_{\nu p}^{NC} = 1.06 \times 10^{-9} \left( \frac{E_\nu}{1 \text{ GeV}} \right)^{0.408} \text{ mb} \]  (1.4)

\[ \sigma_{\nu p}^{CC} = 2.69 \times 10^{-9} \left( \frac{E_\nu}{1 \text{ GeV}} \right)^{0.402} \text{ mb} \]  (1.5)

where the neutrino energy \( E_\nu \) should be given in the lab system. The total neutrino nucleon cross section is given in Figure 1.1.

1.5 Neutrino astronomy

Neutrinos are one of the main components of the cosmic radiation in the high energy regime. Recent studies make compelling arguments that input from neutrino observations will be necessary to resolve the UHECR problem[8]. Neutrinos are coupled to the highest energy cosmic rays both as a direct byproduct, and perhaps as a potential source of them. The study of physics or astrophysics of UHECR is intimately linked with the

\[ 21 \text{ b}(	ext{barn}) = 10^{-28} \text{ m}^2, \text{ mb}=\text{milli barn} \]
1.5. Neutrino astronomy

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.

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. in 1965[9] 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 $\sim 50$ kHz to $\sim 550$ MHz (for mean energy $10^{16}$ eV) have been studied extensively by different groups all over the globe[10] [11] in a period of almost five decades since 1965. From the middle of this period, some laboratories are being engaged in detection and investigation of Giant Air Showers (GAS) with $E_p > 10^{19}$ 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 has given birth to UHE neutrino astronomy based on radio
1.5. Neutrino astronomy

methods. It is worth mentioning that theoretical prediction by Askaryan in 1965\cite{12} of negative charge imbalance in electron-photon cascade produced by a HE particle in a dense medium forms the base of radio astronomical method (RAM) of neutrino detection. Experimental confirmation of Askaryan effect in 2000\cite{13,14} 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 ($E_p \sim 10^{20} \text{eV}$) cosmic rays are bent in intergalactic magnetic fields. Since they only interact weakly, neutrinos do not suffer from 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.

There are several theoretical predictions that cosmic neutrinos are produced by accelerated protons within high-energy astrophysical objects such as Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRBs). Neutrinos can propagate in straight lines through the universe as they are not effected by magnetic fields of the galaxy and essentially do not interact with particles on the way to the earth. UHE neutrinos are expected to play a key role in connecting the observed UHE cosmic-rays to their birthplaces, which may shed light on the long standing puzzles of the origin of UHE cosmic-rays.

To study the highest energy cosmic particles and 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 alternative for neutrino and possibly cosmic ray 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.

This thesis presents the feasibility of utilizing the Transition Radiation (TR) produced by UHE neutrinos and CRs in different di-electric media viz. air, Antarctic ice and
lunar regolith, as a tool for radio detection of UHE particle. 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.

A review on theoretical as well as experimental works on RE done at various labo-
ratories all over the globe till date is presented in the next chapter.
Bibliography


