The Radio Cerenkov Technique for Ultra-High Energy Neutrino Detection

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Abstract

I review the status of the Radio Cerenkov detection technique in searches for ultra-high energy (UHE) neutrinos of cosmic origin. After outlining the physics motivations for UHE neutrino searches, I give an overview of the status of current and proposed experiments in the field.

Key words: neutrino, radio, ultra-high energy, cosmic ray, Cerenkov

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1 Introduction

Over the past century, cosmic radiation from sources outside the earth’s atmosphere has been measured over 14 orders of magnitude in energy. At $10^{18}$ eV, cosmic rays are incident on the earth’s atmosphere at a rate of one particle/km$^2$/year. Cosmic ray experiments HiRes and Auger [1] both see a break in the spectrum near $10^{19.5}$ eV and this was expected; at this energy, protons and heavy nuclei reach their threshold for interacting with cosmic microwave background (CMB) photons through what is known as the Greisen-Zatsepin-Kuzmin (GZK) process [2]. This process can, for example, occur through a $\Delta$ resonance:

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^* \rightarrow n \pi^+ \rightarrow n e^+ \nu_\mu \nu_e \bar{\nu}_\mu$$ (1)

The GZK process slows a cosmic ray above threshold within approximately 50 Mpc of its source. Above a few TeV, gamma rays too are absorbed before reaching us, but in the infrared background radiation through pair production [3].
While the GZK process prevents us from observing distant cosmic rays above the cutoff, the same process is a source of neutrinos, as seen in Equation 1 which can travel cosmic distances unattenuated. In addition, any photoproduction process that produces cosmic rays within an astronomical source would be expected to produce neutrinos from the decay of charged pions. Figure 1 includes a range of models for the expected neutrino flux from the GZK process in the UHE region and current limits on diffuse neutrino fluxes.

To date, the only observed sources of neutrinos outside of the earth’s atmosphere have been the sun [4] and Supernova 1987a [5]. No diffuse cosmic neutrino flux has been measured, though such a measurement is crucial to a complete picture of the UHE universe. Neutrinos are the only messengers above $10^{19.5}$ eV that can probe distances greater than hundreds of Mpc. Un-deflected by magnetic fields, neutrinos point back to their place of origin, and above $10^{17}$ GeV would produce interactions with center-of-mass energies exceeding that of typical interactions at the LHC.

Several experiments are searching for a cosmic flux of neutrinos by detecting the visible Cerenkov radiation produced by particle tracks [6], the largest being the AMANDA-II experiment and its km$^3$ successor IceCube [7]. Their observations are consistent with the expectation from atmospheric neutrino background. They constrain the neutrino flux below $10^{18}$ eV.

## 2 Radio Cerenkov

At and above $10^{18}$ eV, the expected neutrino flux is too small to be detectable in the km$^3$-size volumes that are characteristic of the visible Cerenkov technique. Although theoretical predictions for neutrino fluxes vary by orders of magnitude, a mid-range model gives approximately 10 neutrinos/km$^2$/year. If a $10^{18}$ eV neutrino interacts in ice within 300 km, we expect 0.03 neutrino interactions/km$^3$/year. Once we account for a typical detector acceptance, the rate becomes one interaction in a km$^3$ detection volume every 100 years.

Radio Cerenkov is the most established neutrino detection technique that has the scalability to sustain an UHE neutrino particle and astrophysics program over the coming decade. The radio Cerenkov signal was predicted by Gurgen Askaryan in 1962 [8]. The signal originates from the net current in a shower rather than from individual tracks. As an electromagnetic shower develops, a 20% charge asymmetry appears as electrons in the medium become part of the shower, and likewise positrons in the shower are annihilated by electrons in the medium. Since the transverse size of the shower is of order 10 cm, the Cerenkov radiation is coherent only for wavelengths longer than that (frequencies $< \mathcal{O} (1 \text{ GHz})$). This effect has been confirmed experimentally in accelerator beam
tests [9].

Askaryan also predicted that at the same frequencies where the radio Cerenkov signal is coherent, long attenuation lengths can be found in media that occur naturally in large volumes such as ice, salt and sand. All past, present and proposed radio Cerenkov experiments use one of these three media. The first experiments to pioneer this technique were: FORTE [10], a satellite antenna system that viewed ice over Greenland, GLUE [11], a radio dish telescope aimed at the sandy regolith on the surface of the moon, and RICE [12][13], an array of radio antennas on AMANDA strings taking data since 1999.

Most current and proposed radio Cerenkov experiments rely on Antarctic ice as their detection medium. This is due to its exceptionally large ice volume, the long attenuation lengths observed at the frequencies of interest, and the existing infrastructure and science programs on the continent. Attenuation lengths in the microwave frequencies were measured in the ice beneath the South Pole in 2004, and were consistent with 1 km for ice at -50°C [14].

3 RICE

RICE (the Radio Ice Cherenkov Experiment) is an array of 16 antennas of bandwidth 200-1000 MHz buried in the Antarctic ice beneath the Martin A. Pomerantz Observatory (MAPO) approximately 1 km from the geographical south pole. The antennas are contained within a cube of ice 200 m on a side with its center approximately 150 m below the surface. RICE is primarily searching for a radio Cerenkov signal from electromagnetic and hadronic cascades induced by UHE neutrinos colliding with nuclei in the ice.

The RICE detector triggers an event if at least four antennas read a voltage above threshold (0.1 to 1 V after amplification) within 1.25 µs. Between 1999 and 2005, RICE’s livetime was $7.41 \times 10^6$ s and recorded $1.035 \times 10^6$ triggers. No candidate neutrino events were found in offline analysis of this data and RICE has derived an upper bound on the flux seen in Figure 1.

RICE would also be sensitive to magnetic monopoles of intermediate mass (IMM’s) much less than the conventional GUT mass near $10^{17}$ GeV. IMM’s have been predicted by Wick et al. [15] to be relativistic with Lorentz factors given by $\gamma = E/M_{\text{IMM}}$ where $E$ is the total energy of the monopole estimated to be $\approx 10^{16}$ GeV. Therefore, the same null result can be used to set an upper limit on a flux of IMM’s if both the IMM energy loss in the ice surrounding RICE and the efficiency for triggering and reconstructing such events can be understood. To model to IMM energy loss, the analysis uses a stochastic model for muon energy loss, replacing the IMM mass for the muon mass
and monopole charge for unit electric charge. From Dirac’s relation for the magnetic monopole charge, \( Z = 1/(2\alpha) \approx 68 \) where \( \alpha = 1/137 \) \cite{16}. RICE constrains the flux of intermediate mass magnetic monopoles to between \( 10^{-19} \) and \( 10^{-18} \) cm\(^2\)/s/str in the range \( 10^8 < \gamma < 10^{12} \) respectively, and at \( \gamma = 10^7 \) the limit is \( 10^{-17} \) cm\(^2\)/s/str. These are the world’s best limits on magnetic monopoles based on direct observations.

4 ANITA

ANITA (ANtarctic Impulsive Transient Array) is an Antarctic balloon-borne experiment that is launched under NASA’s long duration balloon program from McMurdo station. It consists of an array of 32 broadband (200-1200 MHz) dual-polarization quad-ridged horn antennas that view the Antarctic ice sheet from its in-flight altitude of 37 km, where it is in view of \( 1.5 \times 10^6 \) km\(^2\) of ice surface. The first full ANITA flight was launched on December 15\(^{th}\), 2006, taking 3 1/2 trips around the continent in 35 days. ANITA II has been approved and is scheduled to fly during the 2008-2009 season. The author of these proceedings is a member of the ANITA experiment.

The ANITA trigger divides the signal into frequency sub-bands and a coincidence requirement provides a powerful rejection against narrow bandwidth backgrounds and thermal noise. A global trigger requires further coincidences across antennas. While ANITA was in view of McMurdo station, calibration pulses were sent to the payload from above and below the surface. These multi-purpose signals allowed us to quantify our resolution on the direction of incident pulses. Preliminary results from borehole pulses show an angular resolution of \( 0.2^\circ \) in azimuth with respect to the center axis of the payload and \( 0.8^\circ \) in zenith angle. This reconstruction has been used to produce a map of the locations of signal sources. Figure \( 2 \) shows such a map produced \textit{with only 10\% of the data set} from an analysis where the remaining 90\% of the data is blinded. Events included in this plot have satisfied the requirements that the voltage exceed three times the thermal noise level, angular reconstruction was successful, and the time profile and Fourier transform are consistent with the expectation for the radio Cerenkov signal. All events in this 10\% data set have been associated with camps, travelers and automatic weather stations. Analysis of the remaining 90\% of the data is in progress. ANITA expects to either be the first to observe UHE neutrinos or set the world’s best limits in its energy range.

A test instrument with two antennas called ANITA-lite was flown in the 2003-2004 Austral summer, piggybacking on the TIGER experiment. ANITA-lite constrained the UHE neutrino flux and ruled out Z-burst models, which could have led to cosmic rays with energies that exceed the GZK cutoff \cite{17,18}. 

4
5 AURA

An experiment embedded in its detection medium, such as RICE, can, with adequate volume, be sensitive to a lower energy regime than experiments where the medium and instrumentation are well separated. Since the expected neutrino spectrum, like the measured cosmic ray spectrum, is steeply falling, a lower threshold is a great advantage in terms of predicted neutrino rates.

AURA (Askaryan Under ice Radio Array) is designed to utilize existing infrastructure and technology for a radio frequency neutrino detector at the South Pole [19]. The system combines RICE antennas, electronics and control interface with the digitizer and triggering designed for ANITA and the main board, data acquisition, boreholes and cables used for IceCube. An AURA cluster consists of four RICE dipole antennas, a Digital Radio Module (DRM) with electronics for performing triggering, digitization and transmitting data to the surface and an Antenna Calibration Unit (ACU) for communications and power between the surface and the DRM. There were three AURA clusters deployed in the 2006-2007 polar season at the South Pole. Single channel and cluster trigger rates have been measured during times when IceCube and AMANDA were idle and also when they were taking data. The combined trigger was found to reduce noise to the level necessary for detector operation. The AURA team plans to continue their efforts to study the radio environment surrounding IceCube, and expand to a shallow UHE neutrino detector.

6 IceRay

Any next-generation UHE neutrino experiment aims to move beyond the discovery stage of the field to an era of particle physics and astrophysics measurements with 10-100 GZK neutrinos/year. The proposed IceRay experiment would be an array of antenna stations deployed near the surface close to the South Pole. With no deep holes needed, the cost could be kept relatively low, but a two-dimensional array near the surface is only sensitive to limited depths and faces complications from the depth-dependent index of refraction in the firn near the surface. An alternative proposal is to expand AURA into a large three-dimensional deep array that would surround IceCube in boreholes dedicated for radio receivers. Preliminary simulations of both IceRay and AURA designs show that an array of either type with 18-36 stations that could be built by 2012 could detect 4-8 neutrinos from the GZK process per year. This would be a precursor to a larger array. One advantage of building a radio array at the South Pole is the possibility of observing events in coincidence with IceCube. The IceRay and AURA designs are both being developed with this very desirable feature in mind.
ARIANNA is a proposed array of antenna stations on the surface of the Ross Ice Shelf [20]. This detector is designed to be sensitive to not only signals observed directly from the shower, but also signals that have been reflected from the bottom of the ice shelf where it meets sea water, at about 600 m depth. This boundary is highly reflective. Sensitivity to reflected signals means a larger range of solid angles in the detector’s acceptance compared with a surface detector where only direct signals are observed. Since the ice is warmer on the ice shelf than on the continent, the attenuation lengths are shorter, but still comparable to the depth of the shelf. In November 2006, S. Barwick and D. Saltzberg measured attenuation lengths on the Ross Ice Shelf greater than 300 m, averaged over all depths, for frequencies in the range 200-1200 MHz. A prototype station has been deployed for one year, powered by solar panels.

SalSA

It has long been proposed that a neutrino detector could be deployed in one of the large salt formations that exist in many locations around the world [21]. This detector concept has been termed Salt Sensor Array (SalSA). One would find 2.5 times as many neutrino interactions per unit volume in salt compared due ice due to its higher density. Although the peak power of the emitted radio Cerenkov signal is lower than in ice, the width of the Cerenkov cone is more broad [22]. Additionally, an experiment in the Northern Hemisphere would view a region of the sky not in view of an experiment at the South Pole, and could also be more accessible. Many salt domes exist in the Southeastern United States and volumes of a few km × few km × 10 km are not atypical.

Ground Penetrating Radar (GPR) experts have reported low radio loss in salt mines in the US, but it is difficult to deduce attenuation length measurements from their findings [23]. Before a SalSA experiment can move forward, long attenuation lengths (>≈ 250 m) must be measured definitively at radio frequencies. Gorham et al. [21] reported attenuation lengths $L > 40$ m at 67% confidence at the Hockley salt mine in Texas. Although their mean fit values were in the region of 200 m, the uncertainties were large, in part due to the short range of transmission, up to 45 m. A team from UCL, UCLA and LSU that includes the author of these proceedings has visited the Cote Blanche salt mine in Louisiana and has transmitted broadband pulses over 300 m and from depths as much as 60 m below the lowest mining level. The results from these data is forthcoming, and this topic remains under active investigation.
9 Conclusions

The field of UHE neutrino detection using the radio Cerenkov technique has become a mature field, with existing experiments beginning to probe the expected neutrino flux from the GZK process. The technique holds the capability of moving beyond the discovery stage and into an era of making particle- and astrophysics measurements with 10-100 UHE neutrinos per year. I have described several proposed projects that are being designed to measure neutrinos rates at that level once operating at full scale.

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Fig. 1. From [17] with recent 90% CL limits from RICE ‘05, Amanda II and AUGER added [13,7,24]. The ANITA curve is an expected limit established pre-flight. The shaded region is a range of expected neutrino fluxes from the GZK process.

Fig. 2. Map of reconstructed source locations from 10% of the data from the ANITA flight. All events in this 10% data set have been associated with camps, travelers and automatic weather stations. Plot by Jiwoo Nam.
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