Detection of UHE-CR using in-ice detectors in South Pole

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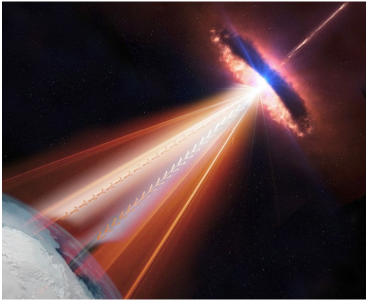
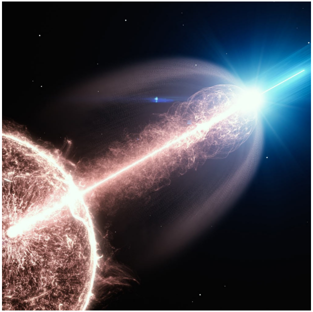
UHE-CR Sources?

- Charge particles coming from the outer space. (Possibly) Originating from most explosive objects like AGNs (Active Galactic Nuclei), GRBs (Gamma Ray Bursts) etc that provides strong magnetic shocks via magnetic field to get the particles accelerated
- The particles remain confined in the sources and accelerated several times before they achieve the high energies





Artistic interpretation of a Blazar by ICECUBE/NASA (left) and a GRB by DESY (right)

Motivation

- Probe cross section at UHE ($E \geq 10$ PeV) regime (beyond LHC)
- Radio signals from UHE-CR cascades acts as important background for in-ice neutrino detectors
- The UHE-CR has higher cross-section and their signals share many similarities with the neutrino signals. Therefore, it supports the detection capabilities of the experiments
- UHE-CR signals could be an interesting calibration sources for the in ice experiments looking for UHEν

Energy based classification

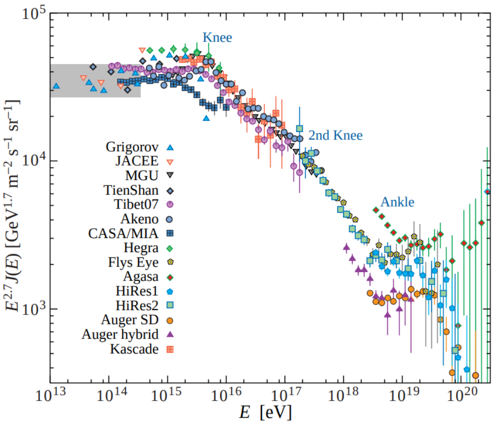
Units: 10^{-3} Joules $\approx 10^{16}$ eV = PeV

- $\leq$ 1 GeV : LR (Low energy)
- 1GeV $\leq$ 1 PeV : VHE (Very High Energy)
- 1PeV$\leq$ 100 PeV : UHE (Ultra High Energy)
- $>$ 100 PeV : EHE (Extremely High Energy)

Radio detection targets UHE $\rightarrow$ EHE sources based on its higher attenuation length

Energy Spectrum

- Almost a power law with four features: $J \propto E^{-\gamma}$ with $\gamma \approx 3$
- Knee: Steepening of the spectrum ($\gamma \simeq 2.7 \rightarrow 3.1$) at $10^{6.5}$GeV
- Second knee: Further Steepening ($\gamma \simeq 3.1 \rightarrow 3.2$) at $10^{8.7}$ GeV
- Ankle: A dip appears ($\gamma \simeq 3.2 \rightarrow 2.7$) at $10^{9.5}$ GeV
- GZK effect: flux drops dramatically for energies $\gtrsim 10^{11}$ GeV



Source: Ref[1]

GZK effect

- Greisen, Zatsepin, and Kuzmin (GZK) predicted that the CMB can make the universe opaque for CR of high energies. E.g for protons, it occurs beyond photopion production threshold and has been confirmed by Telescope Array and Pierre Auger Observatory(Ogio, 2019; Castel-lina, 2020)

$$E^{th}_{P\gamma_{CMB}} = \frac{m_p + m_{\pi}/2}{\omega_{CMB}} \simeq 6.8 \times 10^{10} \left(\frac{\omega_{CMB}}{10^{-3} eV}\right) \text{GeV} \qquad \omega_{CMB} \sim 10^{-3} \text{ eV (typical } \gamma_{CMB})$$

- In simple words: as the source of the distant CR becomes larger $\rightarrow$ more CMB fog will come into their way$\rightarrow$ greater likelihood of scattering or being absorbed by CMB fog
- The distance scale for protonic cosmic rays interactions(where it losses 95% of energy) is around 10Mpc

$$p^+ + \gamma_{CMB} \rightarrow \Delta^+$$

$$\Delta^+ \rightarrow p^+ + \pi^\circ \rightarrow p^+ + 2\gamma$$

$$\Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \mu_\nu$$

Development of EAS

- primary CR $\rightarrow$inelastic collision $\rightarrow$ air nucleus (mostly O, N) $\rightarrow$ secondary particles/particle shower like baryons(p, n..), mesons(π, K..), and leptons(e, μ..)
- $\pi^\circ \rightarrow 2\gamma$, $\gamma \rightarrow e^+ + e^- \rightarrow$ More photons EM part of Shower
- $(\pi^\pm, K^\pm) \rightarrow$ hadronic component of the EM shower
- $\pi^\pm$ almost exclusively decay into muons and neutrinos

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- The particle number decreases as the critical energy point has been passed

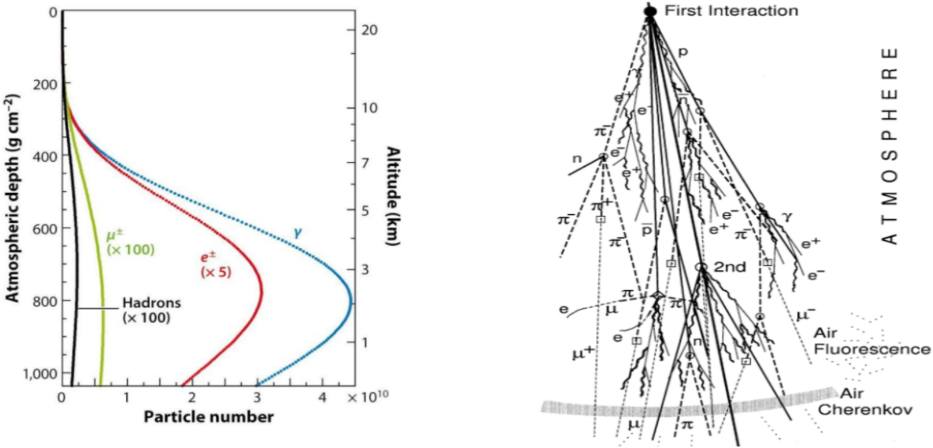
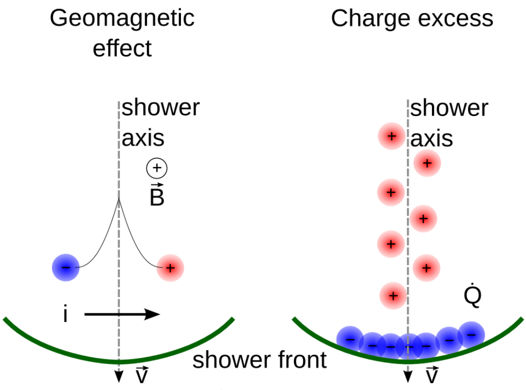


Figure: Schematic view of a EAS(left) and evolution of the most dominant particles in the shower(right): Adopted from Uzair's thesis

Radio emission from EAS

- Two mechanisms cause EAS to emit radio signal:(i) Askaryan effect (ii) Geomagnetic effect
- particle cascade $\rightarrow$ ionizes medium. Two phenomenon contributes for the 20% net negative-charge at the shower front (i) Compton's scattered atomic electrons (ii) positron depleted due to annihilation. This negative charge moves faster than the speed of light in the medium $\rightarrow$ emits coherent Cherenkove Radiation at radio wavelengths (G. Askaryan, 1962)
- Interaction of earth's magnetic field with particles $F = q(E + v \times B)$ causing a transverse current along the shower front. As they spiral, the particles emit synchroton RF signals



Askaryan effect (right) and geomagnetic effect (left). Source: Ref[2]

How can we differentiate?

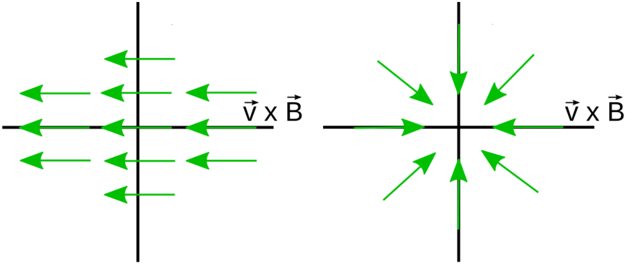
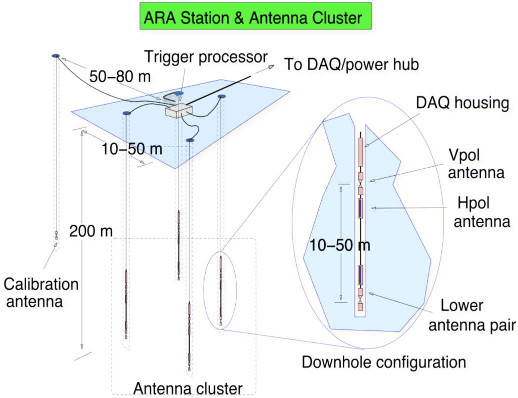


Figure: Geomagnetic effect (left) and Askaryan effect (right): Source Ref[2]

- polarization direction plays important role to differentiate the signal of the two processes
- Geomagnetic effect : Lorentz force , polarization is orthogonal to the shower axis and magnetic field
- Askaryan effect: polarization direction is toward the shower axis

Radio wave in-ice detectors?

- Around 200 MHz to 1 GHz sensitive in-ice antennas are used
- Two classes of the detectors at the energy range PeV to EeV
- First class includes the experiments like ARA, ARIANA , and RNO-G. The first two are deployed in South Pole and last one is in the Greenland. All are capable to detect the Askaryan radiation.
- Second class of experiment aims to detect particle cascade via radar echo method. The radio waves are thrown to the in-ice particle cascade and the reflected signals are recorded to analyzed the cascade. Greenland based RET-CR is currently working using this method Ref[3].



A typical ARA station. Source: ARA website

RICE (with 20 channels) was the first in-ice detector deployed in South Pole in 1995

CR Simulations: FAERIE

- FAERIE (the Framework for the simulation of Air shower Emission of Radio for in-Ice Experiments) is the first complete Monte-Carlo CR radio emission simulation $\rightarrow$ deals with both the propagation of particle cascade in air and in ice , and calculates the expected radio emission Ref[3].
- It is an integrated frame work of CORSIKA 7.7500 and GEANT4 simulations
- CORSIKA 7.7500 simulates for the in air particle cascade and calculate the radio emission using CoREAS.
- CoREAS applies the endpoint formalism to calculate the electric field at a given antenna location in air. It takes care of every single charge in the particle cascade during the CORISKA simulation
- Ray tracing technique has been used to trace the in ice antenna position
- Study of in ice particle cascade is done by GEANT4 simulations. It allows for full Monte-Carlo simulation of particle creation and propagation through any given medium
- It incorporates the varying index of refraction for both air and ice with altitude and depth respectively

Simulated AES

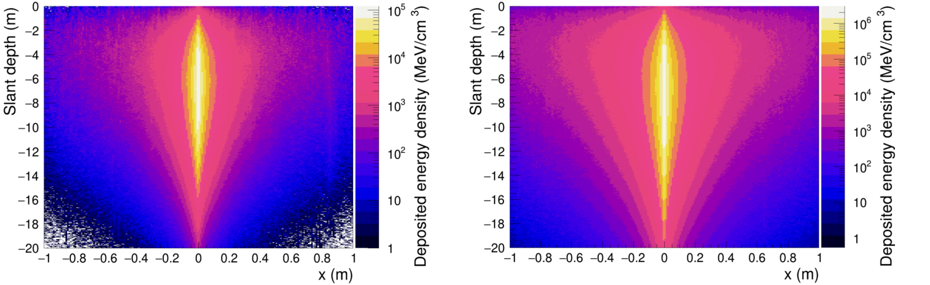
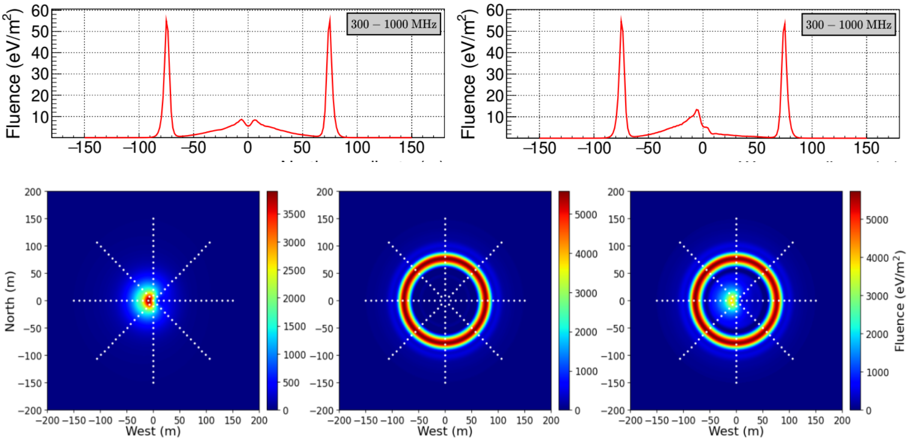


Figure: simulated showers with energy 10^{17} eV (left) and 10^{18} eV (right) with zenith angle 0 deg. Adopted from Ref[3]

- Explains the deposited energy density in ice by in ice particle cascade within a vertical 1cm wide slice going through the center of particle shower for the particular primary energy

Double pulse?



A combined effect of in-air and in-ice emission. Used 201 antennas each on N and W axis taking antenna spacing of 1.5 m, E= 1e17 eV, and $\theta = 0^\circ$ Ref[3].

E-field

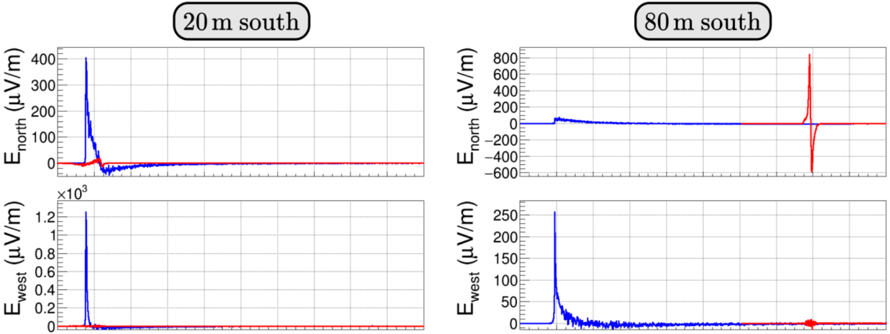


Figure: E-field vrs time for two different antennas, located at West axis at a depth of 100m, E = 1e18 eV, $\theta = 0°$, the red is for in ice and blue shows in air emission Ref[3]

What is next?

- Will be trying to include the detector response and make a search for real events based on the template match filtering

Refrences

- L.A. Anchordoqui, ultra high-Energy Cosmic Rays: Facts, Myths and Legends, University of Wisconsin-Milwaukee
- Zur Erlangung, Radio detection of ultra high energy cosmic rays, KIT , 2017
- Simon et al, Simulations of radio signals from cosmic ray cascade in air and in ice as observed by in-ice Askaryan radio detectors, 2024