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# Radio Pulse Emission in Air Showers and Dense Media

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The different radio frequency (RF) pulse generating physics processes will be explored with the primary distinction between the air shower emission and the Askaryan emission in dense materials. During the 1960s and 1970s, Cosmic Ray physics saw a flurry of activity surrounding the radio emission of air showers. These kinds of experiments eventually ended because of difficulties in measuring signals and interpreting results. Interest in radio detection has been renewed in part due to the Askaryan effect, which predicted that the radio signal becomes dominant for showers in dense, radio transparent material such as ice, salt, or lunar regolith.

## 1. Introduction

It has been known for several decades that cosmic ray showers emit radio signals as they propagate through materials. However, the physics behind radio pulse generation in air is vastly different from that of dense materials such as ice. Historically, experiments focused on RF emission in air showers first, whereas experiments on radio emission in salt, ice, and lunar rock have only been developed in the past few years, despite work by G.A. Askaryan on the physics of radio emission in dense materials in the early 1960s.

Early exploration of RF emission in air showers was embraced as an inexpensive way to explore cosmic rays with a guaranteed signal. However, experiments such as Jodrell Bank and Haverah Park in the 1960s had mixed results, due in part to the radio-loud photomultiplier tubes that were used as coincidence detectors. Over the past few decades, detector technology has dramatically improved, allowing the topic to be revisited. More recent experiments include Rosner et al.'s coincidence experiment to the Chicago Air Shower Array (CASA) from the 1990s; currently, LOFAR Prototype Station (LOPES); and Low Frequency Array (LOFAR), which is in development.

The theory of radio emission in dense materials was formulated by Askaryan in 1962, at approximately the same time as the early air shower experiments. Despite this, it had not been tested until very recently by accelerator measurements performed at SLAC using silica sand in 2000 [2] and again in using salt in 2002. [11] Once the so-called Askaryan effect was confirmed, experiments searching for ultra-high energy neutrinos via radio emission in dense materials began to develop. The first such experiment was the Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE) in 1999. [12] Radio Ice Cherenkov Experiment (RICE) is currently under operation [10]; ANtarctic Impulsive Transient Antenna (ANITA) successfully launched a prototype ANITA-LITE in 2003 and is set to fly a full-scale version of the experiment in 2006. [16] Finally, Salt dome Shower Array (SalSA) is currently under development. [11]

## 2. The Physics of Radio Emission in Air Showers

Before the 1960s, most experiments detected cosmic rays via scintillators and photomultiplier tubes in optical frequencies. After Galbraith and Jelley discovered extensive air showers (EAS) were accompanied by Cherenkov radiation in the 1950s, Jelley questioned if the radiation extended to radio frequencies, and thus whether or not current optical detectors could be supplemented with radio detectors. Kahn and Lerche, and later Colgate, showed that coherent Cherenkov radiation was not necessarily the source of these radio signals. [3] If it were, the shower would have a pronounced charge imbalance, created by an excess of electrons. Instead, the dominant source is likely due to the Lorentz force, which separates positive charges from negative charges in the shower, creating a dipole effect. This effect basically remains over the lifetime of the shower, initiated again and again as new generations of particles are created in the shower. [3] The radiation produced is "Cherenkov-like" [3] even though there is no numerical charge excess. There are other possible sources which could contribute to the detected signal, albeit less than the dipole mechanism described above. The shower could carry an excess of charge via the Compton effect, though the effect is not as strong as it is in dense materials. [5] Also, air showers can ionize the atmosphere, which would generate a signal as it moves through the Earth's electric field. [14] Ultimately, regardless of how it is produced, the signal is coherent because the dimensions of the shower are less than the wavelength of the radio emission. The coherence is at a maximum before the shower maximum, which implies that the radio signal is strongest before and during the maximum. After this point, energy dissipation causes the signal to lose coherence. [4]

Clearly, the exact theory is not well understood. As Falcke and Gorham describe, the process can be thought of as "coherent geosynchrotron emission"; they demonstrate that it is not inconsistent with Kahn, Lerche, and Colgate's formulation of the radio signal production. [4] Falcke and Gorham are able to use the geosynchrotron model to roughly calculate observed radio emissions to within an order of magnitude of observed air showers. Further evidence in support of the geomagnetic formulation is that the emission is strongly polarized in the "geomagnetic E-W direction." [4] While it is not clear that coherent geosynchrotron emission is the only component of the radio signal, convincing arguments such as these point to it as a dominant part.

Early experiments also had problems analyzing results. For instance, there are conflicting results of the constant $s$ associated with the field strength per frequency $\varepsilon_\nu$

$$\varepsilon_\nu = s\,(E_p/10^{17}\ eV)\,\sin\alpha\cos\theta\,\exp(-R/R_0)\quad \mu V\,m^{-1}\,MHz^{-1} \qquad (1)$$

where, according to Rosner, $s$ is a constant, $E_p$ is the energy of the primary particle in eV, $\alpha$ is the angle between the axis of the shower and the Earth's magnetic field, $\theta$ is the zenith angle, $R$ is the perpendicular distance to the shower core at its closest approach, and $R_0$ is an increasing function of frequency and $\theta$. Past experiments at Haverah Park and in the former U.S.S.R. found values of $s$ = 1.6 (0.6 μV $m^{-1}$ $MHz^{-1}$) and $s$ = 9.2 (3.4 μV $m^{-1}$ $MHz^{-1}$), respectively. [5] More recently, Rosner et al.'s radio experiment at CASA set an upper limit of $s$ = 54 μV $m^{-1}$ $MHz^{-1}$, unable to derive a more exact result due to non-detection of events. [5] In their Monte Carlo simulation, Huege and Falcke found $s$ = 13 μV $m^{-1}$ $MHz^{-1}$. [15]

LOPES has been able to detect radio signals from cosmic rays in the 43-73 MHz band. Its success is due in part to improvements in technology; it has the capability to resolve time intervals of about 30 ns, whereas older experiments had resolutions on the order of 1 μs. [1] LOPES does not have the proper gain calibration to report a value of $s$. However, it has been able to observe a signal in accordance with Falcke and Gorham's coherent geosynchrotron emission model. [1]

## 3. The Physics of Radio Emission in Dense Materials

In dense materials such as ice, salt, or rock, the development of the radio signal is much different than the processes described above. Again, coherence of the signal is due to the fact that the wavelength of the radiation is long compared to the dimensions of the shower. [6] This also allows the signal to be coherent for a much larger range of frequencies than in air. Air showers have dimensions of a few kilometers and are coherent up to about 10 MHz whereas in dense materials, the shower has dimensions on the order of a meter, and is coherent up to about 10 GHz (however, materials such as ice are only radio-transparent up to about 1 GHz). [7] Cherenkov radiation, the dominant source of radio emission in dense materials for ultra-high energy particles, develops here as a result of a ~20% excess of charge from positron annihilation and Compton scattering of shower electrons. The process is facilitated by the density of the material, and is far stronger than any such effect in air. [8] This effect also dominates other emissions such as optical Cherenkov radiation or fluorescence for energies above about $10^{16}$ eV, making it well suited to the observation of UHE cosmic rays. [9] This is because the energy of *visible* Cherenkov radiation $E_C$ is proportional to the energy of the primary particle $E_P$, but that $E_C$ is proportional to $E_P{}^2$ for *radio* Cherenkov radiation. If the primary particle (in this case, a neutrino) has high enough energy, radio Cherenkov dominates the emission. [8]

Despite the fact that Askaryan predicted this effect in the early 1960's, experimental evidence was not obtained until nearly 40 years later by Saltzberg et al. in accelerator measurements at SLAC with a silica sand target [2] and again with a salt target. [11] The existence of the Askaryan effect was confirmed via "measurements of the polarization, coherence, timing, field strength vs. shower depth, and field strength vs. frequency" and also showed that the observed signal is "inconsistent with radiation from geomagnetic charge separation as observed in extensive air showers." [2]

Several experiments have been developed recently that use the Askaryan effect to observe ultra-high energy neutrinos in ice, salt, and lunar regolith. The Radio Ice Cherenkov Experiment (RICE), with an effective volume of 15 $\text{km}^3$ sr, operates at the South Pole in conjunction with AMANDA, consisting of a "16-channel array of dipole radio receivers" embedded in Antarctic ice. [10] RICE was able to set limits on electron neutrino fluxes, even though no neutrino events were detected. It also demonstrated its ability to reject "anthropogenic backgrounds and thermal noise." [10]

The Goldstone Lunar Ultra high energy neutrino Experiment (GLUE) observed the lunar regolith with large antennas at the Goldstone facility in California, looking for microwave Cherenkov emission from neutrinos incident on the moon. Even with only 120 hours of livetime, GLUE was able to provide constraints on the Z-burst model of neutrino fluxes due to the sheer volume of lunar regolith available—on the order of 100,000 $\text{km}^3$. [12]

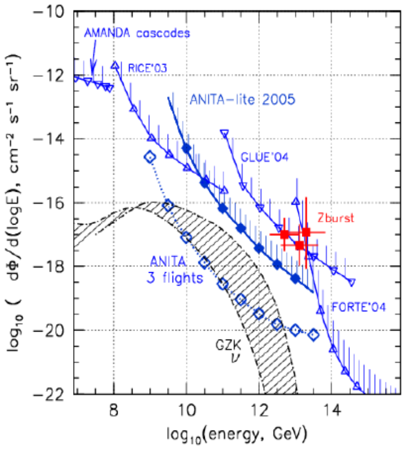

**Figure 1.** Neutrino fluxes constrained by AMANDA, RICE, GLUE, FORTE, and ANITA-LITE, plus predicted GZK fluxes and projected ANITA results. Courtesy of the ANITA collaboration. [17]

Antarctic Impulsive Transient Antenna (ANITA), is a balloon-borne experiment that also uses radio Cherenkov emission in Antarctic ice to detect ultra-high energy neutrinos with an effective volume of $10^6$ $\text{km}^3$. ANITA-LITE, a prototype of ANITA, was launched on December 17, 2003 and flew for 18 days, piggybacked on the TIGER balloon payload. [16] The flight successfully showed that Antarctica is a suitably RF-quiet environment for neutrino detection, and provided a test of detector design. Figure 1 shows ANITA-LITE's constraints on neutrino fluxes as related to the neutrino flux from the Z-burst model, which, when taken with GLUE [12] and FORTE [13] results, rules it out entirely. [17] The full-scale version of ANITA will be the first neutrino experiment with enough sensitivity to effectively probe GZK neutrinos, also shown in figure 1. Its first flight is scheduled for December 2006. [16]

Salt dome Shower Array (SalSA) is a proposed experiment that will look for UHE neutrinos in salt domes. Saltzberg et al.'s accelerator tests performed in June of 2002 successfully confirmed several properties of the Askaryan effect in salt, including coherence and polarization of the signal. [11] A salt-based neutrino experiment is attractive because of the accessibility of large salt domes and because such an experiment could run continuously. "For a system with a design lifetime of 10 years or more, even minimal GZK neutrino fluxes will produce a rich data sample of events which would allow good precision on estimates of the GZK neutrino energy spectrum and sky distribution." [11]

## 4. Conclusions

Radio emission in air showers and dense materials are two very different processes that are generated in different ways. In air showers, the signal may be caused by a separation of charge from geomagnetic fields that induce a dipole effect in the shower. This creates a "Cherenkov-like" radiation that is coherent before and during the shower maximum, up to about 10 MHz. In fact, this signal has been shown by Falcke and Gorham to be consistent with "coherent geosynchrotron emission." In dense materials, however, the signal is due to Cherenkov radiation that is generated by a numerical negative charge excess. Because materials like salt, ice, and lunar regolith are much more dense than air, the shower dimensions are much smaller and thus coherent up to the GHz scale. Because of these physical differences, experiments for air showers and showers in dense materials must be approached very differently. Early radio air shower experiments were plagued with problems, leading to a loss of interest in the field. However, interest has been reawakened due to the rediscovery of the Askaryan effect as a new and potentially useful way to use radio emission from ultra high-energy cosmic rays. Also, advances in technology have resolved some of the old difficulties of detecting air shower radio signals, allowing new experiments to develop.

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