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Towards Teraton EeV Neutrino Telescopes

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Abstract. The highest energy cosmic rays provide compelling evidence for EeV neutrino sources, if we can achieve the Teraton target volumes needed. At 10 TeV energies and above neutrino astronomy is in fact the only astronomy with a clear view of the whole universe. Radio detection of neutrino cascade interactions in ice and other solid dielectric media, via the Askaryan effect, provide a realistic path toward this goal.

1. Introduction

At energies above $\sim$ 10 TeV, the universe becomes opaque to photons due to pair production with infrared background photons. At PeV gamma-ray energies, even the galactic center is out of reach. Thus traditional extragalactic photon astronomy ends at energies that are already being probed by ground-based air Cherenkov detectors. We can be certain, however, that there are in fact astrophysical sources up to ZeV (10^{21} eV) energies, since we see nucleons of these energies in cosmic rays. Nucleons at these extreme energies suffer the same kinds of losses as photons however, with the 3K background photons providing an apparent gamma-ray beam in the rest frame of the propagating nucleon. The mean free path for interactions of these particles is less than 10 Mpc, which sets the scale for the GZK horizon (Greisen 1966), the limiting distance over which a source can realistically irradiate its environment, to be of order 50 Mpc. Very bright sources, such as gamma-ray bursters, may extend their effects over a larger distance.

If the observed events are due to the punch-through exponential tail of a cosmologically distributed set of ultra-high energy sources, as the best current models suggest, then a flux of ultra-high energy neutrinos, integrated from all sources out to the earliest epoch of production, is expected in all models. This cosmogenic GZK neutrino flux is likely to be the strongest of any "guaranteed" source. It depends only on the known physics of the $p\gamma$ interactions, cross sections at center-of-momentum energies that are measured already, and the decay of the pions that result from the GZK interactions of the cosmic-ray nucleons.

Current GZK neutrino models (Engel et al. 2001) predict that the energy fluence peaks in the EeV regime, where the neutrino deep-inelastic scattering cross section on nuclear targets has risen to the point where a cubic km of water has a respectable (for neutrinos) 0.2% quantum efficiency. This relatively high interaction efficiency combined with the lack of any atmospheric neutrino

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background makes the GZK neutrino flux an attractive goal for next generation neutrino telescopes. If one takes a conservative view of neutrino source models, GZK neutrinos may be the *only* ultra-high energy neutrino flux accessible in the near future. Their detection and characterization is scientifically compelling, since they provide the only unattenuated tracer of the sources of the ultra-high energy cosmic rays, and their spectral shape is sensitive to the distribution and evolution of the parent population.

The outstanding difficulty with the detection of these GZK neutrinos is the extremely low rate. A cubic km water or ice Cherenkov detector may only expect to detect of order 0.2 events per year per 2π ster. To reliably detect of order 30 events per year, a Teraton (1000 cubic km water equivalent) is required. This is beyond any realistic scaling of existing or planned Cherenkov detectors such as AMANDA, IceCube, or planned ocean detectors such as ANTARES or NEMO. A more cost-effective approach to ultra-large detection arrays is needed. Fortunately, the recent confirmation of the Askaryan effect–coherent radio Cherenkov emission from cascades within dielectric media–appears to provide the new approach needed to achieve the required sensitivity. In this report we summarize these new developments and several experimental initiatives which seek to exploit them.

2. Askaryan Effect.

The concept of detecting high energy particles through the coherent radio emission from the cascade they produce can be traced back nearly 40 years to Askaryan (1962;1965), who argued persuasively for the presence of strong coherent radio emission from these cascades, and even suggested that this property could lead to neutrino detection by an array of antennas that sensed emission from upcoming events within the radio-transparent outer ~ 10 m of the lunar regolith. Askaryan noted that any large volume of radio-transparent dielectric, such as an ice shelf or a geologic saltbed, could provide the target material for such interactions and radio emission. In fact all of these approaches are now being pursued (cf. table 1).

Askaryan's prediction was based on a simple analysis of electromagnetic showers in dense media. He noted that Compton scattering of electrons by gamma-rays within the shower, combined with electron+positron scattering processes and positron annihilation would lead to a $20-30\%$ net excess of electrons over positrons in the shower. At high energies where the total number of e^+e^- is very large, this net charge can radiate coherently at wavelengths longer than a few cm for solid media, since the charge bunch becomes small compared to the wavelength. At EeV energies, where the charge excess approaches 10^9 e^-, the emitted radio power, which scales quadratically with particle number (and thus also with shower energy), dominates all forms of secondary radiation from the shower.

The effect has now been confirmed in accelerator measurements using showers from GeV photon bunches with total (composite) energies in the EeV regime. Such measurements are valid since the effect arises mostly from the region near shower maximum, where particles are at energies below ~ 100 MeV. Two experiments have been reported recently along these lines, the first at the Argonne

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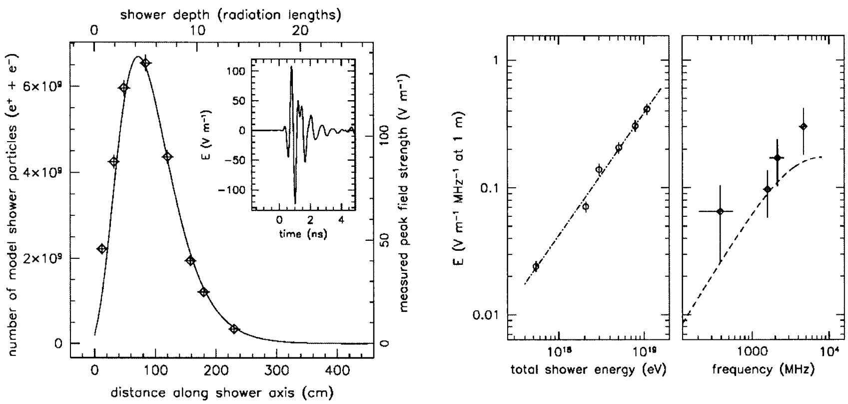

Figure 1. Shower profile and radio coherence for Askaryan effect.

Wakefield Accelerator (AWA) in the fall of 1999 (Gorham et al. 2000), and more recently at the Stanford Linear Accelerator Center (SLAC) in the summer of 2000 (Saltzberg et al. 2001) by SLAC experiment T444. In the latter experiment, unambiguous confirmation of the Askaryan effect was obtained.

Fig. 1 shows a measured pulse profile (inset) and a set of measured peak field strengths for pulses taken at different points along the measured electromagnetic shower. The plotted curve shows the expected profile of the total number of particles in the shower, based on the Kamata-Nishimura-Greisen approximation, and the data points are measured radio pulse amplitude. Clearly the radio pulse strengths are highly correlated to the particle number profile. Since the excess charge is also expected to closely follow the shower profile, this result is consistent with Askaryan's hypothesis. Several other strong confirmations of the Askaryan effect were also observed in T444, including 100% linear polarization, complete coherence, and a characteristic rising Cherenkov spectrum for the radiation.

3. Experiments.

Table 1 indicates experiments which exploit the Askaryan process for radio detection of neutrinos. Several are presently in operation, although none of the currently running experiments has enough reach to constrain the GZK neutrino flux. However, two planned experiments, ANITA and SALSA are aimed specifically at this goal and will likely begin to significantly constrain or characterize this flux within several years.

ANITA will employ a balloon-borne antenna array at an altitude of near 40 km to simultaneously observe of order 10^6 km^3 of Antarctic ice for EeV Askaryan pulses. Because the acceptance solid angle is small, the net exposure in one 30 day flight is a few percent of the Teraton×sr×yr goal, but is enough to begin to constrain the highest GZK flux models, and may detect a few events from even conservative flux models. It is a very cost-effective approach toward getting an initial snapshot of the flux, at present it is approved for a budget

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Table 1. Completed, active, or planned efforts exploiting the Askaryan effect.

Experiment/ acronym	Operation/ status	instrument & location	frequencies (GHz)	Energy range (eV)	exposure 10^{12} *ton sr yr*
Parkes(1)	1994	64m antenna	1.2-1.7	10^{20-21}	0.01
RICE(2)	1997-now	Antarctic sub-ice	0.2-0.4	10^{16-19}	10^{-4}
GLUE(3)	1999-now	70m+34m antennas	2.2-2.3	10^{20-23}	0.1
FORTE(4)	1997-now	LEO satellite	0.03-0.05	10^{22-24}	~ 1
ANITA(5)	2006-07	Antarctic balloon	0.2-1.2	10^{18-21}	0.02
SALSA(6)	2007–	salt-dome	0.1-0.5	10^{17-20}	0.3/yr

(1) Hankins et al. 1996, MNRAS 283, 1027

(2) Radio Ice Cherenkov Experiment, cf. Besson et al. Astropart. Phys. 2003, in press.

(3) Goldstone Lunar Ultra-high energy neutrino Experiment, Gorham et al., Proc. RADHEP 2000.

(4) Fast On-orbit Recorder of Transient Events. This satellite was launched by Los Alamos as a testbed for international treaty verification. Recent data analysis has focused on exposure over the Greenland ice sheet as a source for high energy neutrino events, cf. Lehtinen et al. 2002, Proc. SPIE conf. 4858, in press.

(5) Antarctic Impulsive Transient Antenna, cf. Gorham et al. 2002 Proc. SPIE conf. 4858, in press.

(6) Saltbed Shower Array, cf. Saltzberg et al. 2002, Proc. SPIE conf. 4858, in press.

under $10M and a launch in the 2006-2007 austral summer. Future ultra-long duration (ULDB) flights could make this technique extremely competitive in the long term.

Further out in this decade, the SALSA experiment will make use of large subterranean salt deposits, which have proven to be extremely transparent to VHF and UHF radio propagation (Gorham et al. 2002), to embed a large array of widely spaced antennas, instrumenting of order 50-100 km^3 water-equivalent of rock salt. This will create a tracking calorimeter of unprecedented size, capable of much more precise measurements of the GZK spectrum over a period of several years.

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