

EXPLORING THE ULTRAHIGH ENERGY NEUTRINO UNIVERSE

D.B. Cline¹ and F.W. Stecker²

¹Physics Dept., UCLA

²Lab. for High Energy Astrophysics, NASA Goddard Space flight Center

Abstract

Executive Summary: Astronomy at the highest energies observed must be performed by studying neutrinos rather than photons because the universe is opaque to photons at these energies. In making observations of neutrinos at energies in excess of 10^{19} eV, one can deduce information about the distribution and time (redshift) history of cosmic rays which may have been accelerated to energies above 10^{20} eV. Very large fluxes of neutrinos at these energies which exhibit a hard spectrum would provide evidence of a phase transition predicted by Grand Unified Theories of electromagnetic, weak and strong nuclear forces which would have occurred as early as $\sim 10^{-35}$ seconds after the big-bang. Alternatively, such fluxes may be evidence of superheavy particles which could make up the mysterious “dark matter” which comprises the bulk of the mass of the universe. Such particles are predicted to have been produced at the end of an inflationary phase of expansion in the very early universe. Neutrinos at energies around 10^{15} eV may be produced in observable quantities by active galaxies from the acceleration of cosmic rays in the vicinities of massive black holes or in relativistic jets produced by these black holes. Cosmological gamma-ray bursts may also be sources of neutrinos at these energies. Neutrinos at such energies may oscillate into the specific species of tau neutrinos which, through regeneration, are capable of travelling through the Earth to produce upward-moving showers of charged particles. At energies in excess of 10^{21} eV, ultrahigh energy cosmic rays can be produced by the interaction of ultrahigh energy neutrinos with the very cold (2 K) neutrinos which are relics of the big-bang. In principle, this phenomenon can be used to study the mass and spatial distribution of the 2 K big-bang neutrinos.

1 HIGH ENERGY COSMIC NEUTRINO SCIENCE

1.1 Neutrinos from Interactions of Ultrahigh Energy Cosmic Rays with the 3 K Cosmic Background Radiation

Measurements from the COBE (Cosmic Background Explorer) convincingly proved that the universe is filled with radiation having the character of a near perfect 3 K black body, which is the cooled down remnant of the hot big bang. Extremely high energy protons (above $\sim 10^{20}$ eV) will collide with photons of this radiation, producing pions. Ultrahigh energy neutrinos (greater than $\sim 10^{19}$ eV) are the main result of the decay of these pions. Using present measurements of the flux of such high energy protons, it can be shown that measurable numbers of high energy neutrinos can be detected using imaging optics aboard satellites looking down at the luminous tracks produced in the atmosphere by showers of charged particles produced when these neutrinos hit the nuclei of atoms in the atmosphere. Such satellite arrays have been proposed with the names OWL (Orbiting Wide-angle Light Collectors) and Airwatch.

1.2 Fossils of Grand Unified Theories and Inflation from the Early Universe

The modern scenario for the early history of the big bang, takes account of the work of particle theorists to unify the forces of nature in the framework of Grand Unified Theories (GUTs). This concept extends the very successful work of Nobel Laureates Glashow, Weinberg, and Salam in unifying the electromagnetic and weak nuclear forces of nature. In GUTs, these forces become unified with the strong nuclear force at very high energies of $\sim 10^{25}$ eV which occurred only $\sim 10^{-35}$ seconds after the big bang. The fossil remnants of this unification are predicted to be very heavy “topological defects” in the vacuum of space. These are localized regions where extremely high densities of mass-energy are trapped. Such defects go by designations such as cosmic strings, monopoles, walls, necklaces (string bounded by monopoles), and textures, depending on their geometrical and topological properties. Inside a topological defect, the vestiges of the early universe may be preserved to the present day. Topological defects are expected to produce very heavy particles that decay to produce ultrahigh energy neutrinos. One can learn about the high energy physics unachievable to collider experiments by studying the neutrino signal from the topological defects. The annihilation and decay of these structures and particles is predicted to produce large numbers of neutrinos with energies approaching the energy of grand unification. It

has been suggested that this process may have produced the highest energy cosmic rays yet observed. The discovery of such large flux of neutrinos with energies near the GUT energy scale would be *prima facie* evidence for grand unification. The GUT energy scale is over 12 orders of magnitude higher than the energies currently available at terrestrial accelerators. It is difficult to imagine that terrestrial accelerators which ever reach this energy scale.

Relicts of an early inflationary phase in the history of the universe can also lead to the production of ultrahigh energy neutrinos. The homogeneity and flatness of the present universe may imply that a period of very rapid expansion, called inflation, took place shortly after the big bang. During inflation, the universe is cold but, when inflation is over, coherent oscillations of the inflation field reheat it to a high temperature. While the inflation is oscillating, a non-thermal production of very heavy particles may take place. These particles may survive to the present as a part of dark matter. Their decays can give origin to the highest energy cosmic rays, either by emission of hadrons and photons, or through production of ultrahigh energy neutrinos. Observation of such ultrahigh energy neutrinos may teach us about the dark matter of the universe as well as its inflationary history.

1.3 Neutrinos from Active Galactic Nuclei

Quasars and other active galactic nuclei (AGN) are most powerful continuous emitters of energy in the known universe. These remarkable objects are fueled by the gravitational energy released by matter falling into a supermassive black hole at the center of the quasar core. The infalling matter accumulates in an accretion disk which heats up to temperatures high enough to emit large amounts of UV and soft X-radiation. The mechanism responsible for the efficient conversion of gravitational energy to observed luminous energy is not yet completely understood. If this conversion occurs partly through the acceleration of particles to relativistic energies, perhaps by the shock formed at the inner edge of the accretion disk, then the interactions of the resulting high energy cosmic rays with the intense photon fields produced by the disk at the quasar cores can lead to the copious production of mesons. The subsequent decay of these mesons will then produce large fluxes of high energy neutrinos. Since the gamma-rays and high energy cosmic rays deep in the intense radiation field of the AGN core will lose their energy rapidly and not leave the source region, these AGN core sources will only be observable as high energy neutrino sources.

Radio loud quasars contain jets of plasma streaming out from the vicinity of the black hole, in many cases with relativistic velocities approaching the speed of light. In a subcategory of quasars, known as blazars, these jets are pointed almost directly at us with their observed radiation, from radio to gamma-ray wavelengths, beamed toward us. It has been found that most of these blazars actually emit the bulk of their

energy in the high energy gamma-ray range. If, as has been suggested, the gamma-radiation from these objects is the result of interactions of relativistic nuclei, then high energy neutrinos will be produced with energy fluxes comparable to the gamma-ray fluxes from these objects. On the other hand, if the blazar gamma-radiation is produced by purely electromagnetic processes involving only high energy electrons, then no neutrino flux will result.

1.4 Neutrinos from Gamma-Ray Bursts

Gamma-ray Bursts (GRBs) are nature's most energetic transient phenomenon. In a very short time of ~ 0.1 to 100 seconds, these bursts can release an energy in gamma-rays alone of the order of 10^{52} erg. They are detected at a rate of about a thousand per year by present instruments. It has been proposed that particles can be accelerated in these bursts to energies in excess of 10^{20} eV, either by shocks or perhaps by photonically driven plasma waves.

It is now known that most bursts are at cosmological distances corresponding to moderate redshifts ($z \sim 1$). If cosmic-rays are accelerated in them to ultrahigh energies, interactions with gamma-rays in the sources leading to the production of pions has been suggested as a mechanism for producing very high energy neutrinos as well. These neutrinos would also arrive at the Earth in a burst coincident with the gamma-rays. This is particularly significant since the ultrahigh energy cosmic rays from moderate redshifts are attenuated by interactions with the 3 K microwave radiation from the big-bang and are not expected to reach the Earth themselves in significant numbers. This attenuation of cosmic rays of ultrahigh energy is known as the Greisen-Zatsepin-Kuzmin (GZK) cutoff.

1.5 Neutrino Oscillations and Neutrino Observations

Recent observations of the disappearance of atmospheric muon-neutrinos relative to electron neutrinos by the Kamiokande group, and also the zenith angle distribution of this effect, may be interpreted as evidence of the oscillation of this weakly interacting neutrino state ("flavor") into another neutrino flavor, either tau neutrinos or sterile neutrinos. A corollary of such a conclusion is that at least one neutrino state has a finite mass. This has very important consequences for our basic theoretical understanding of the nature of neutrinos and may be evidence for the grand unification of electromagnetic, weak and strong interactions.

If muon neutrinos oscillate into tau neutrinos with the parameterization implied by the Super-Kamiokande measurements, then the fluxes of these two neutrino flavors observed from astrophysical sources should be equal. This is because cosmic neutrinos

arrive from such large distances that many oscillations are expected to occur during their journey, equalizing the fluxes in both flavor states.

On the other hand, if these oscillations do not occur, the fluxes of tau neutrinos from such sources should be much less than those of muon neutrinos. This is because muon neutrinos are produced abundantly in the decay of pions which are easily produced in cosmic sources, whereas tau neutrinos are not.

Thus, by looking for upward moving showers from tau neutrinos, which can propagate through the Earth through regeneration at energies above 10^{14} eV, one can test for the existence of neutrino oscillations. For large mixing angles between neutrino states, the detection of 10^{14} eV tau-neutrino induced upward-moving atmospheric showers from the direction of a cosmic source such as an active galaxy or gamma-ray burst at a distance of 1 Gpc would occur for a difference of the squares of the mass states as small as $\sim 10^{-17}$ eV², providing an extremely sensitive test for oscillations between neutrino states with extremely small mass differences.

Another important signature of ultrahigh energy tau neutrinos is the “double bang” which they would produce. The first shower is produced by the original interaction which creates a tau particle and a hadronic shower. This is followed by the decay of the tau which produces the second shower bang. The two bangs are separated by a distance of $\sim 91.4 \mu\text{m}$ times the Lorentz factor of the tau.

1.6 Z-bursts from Neutrinos and Ultrahigh Energy Cosmic Rays

1.6.1 Ultrahigh Energy Cosmic Rays

The quest for higher and higher energy cosmic rays goes forward undeterred by the expectation that protons above 10^{20} eV from sources farther away than ~ 100 Mpc should be strongly depleted by interactions with the 3 K photons which make up the cosmic background radiation from the big-bang. Some cosmic rays at these energies have already been detected with ground-based observatories such as AGASA (Akeno Giant Air Shower Array) and Fly’s Eye. Satellite observatories such as OWL/Airwatch would increase the number to thousands and may allow the detection of cosmic rays above $\sim 10^{21}$ eV, if such cosmic rays exist. The detection of thousands of events would enable OWL/Airwatch to obtain an energy spectrum covering an interval where different acceleration and topological defect scenarios make different predictions of the energy spectrum.

OWL/Airwatch also has the unmatched capacity to map the arrival directions of cosmic rays over the entire sky and thus to reveal the locations of strong nearby sources and large-scale anisotropies, this owing to the magnetic stiffness of charged particles of such high energy. Thus, OWL/Airwatch can investigate energy spectra

of any detected sources and also time correlations with high energy neutrinos and gamma-rays.

1.6.2 Z-burst Neutrinos

An exciting possibility is that the highest energy cosmic-ray events observed above the GZK cutoff energy provides indirect detection of the relic neutrinos predicted in standard big bang cosmology. The observed thermal 3 K cosmic microwave background (CMB) permeates the universe as a relic of the big-bang is accompanied by a 2 K cosmic neutrino background of the same thermal big-bang origin. It has been proposed that high energy neutrinos interacting within the GZK attenuation distance with the copious 2 K blackbody neutrinos and annihilating at the Z-boson resonance energy can produce the observed “trans-GZK” air-shower events. This is a possible solution to the problem of how can cosmic rays of “trans GZK” energies (above the GZK cutoff), which are observed to interact in our atmosphere and produce giant air showers, get here from the extragalactic sources which may be many absorption lengths away, (*i.e.*, hundreds of megaparsecs). This is because high energy neutrinos, which may originate at such large distances throughout the Universe, can reach the Earth or nearby parts of the Universe and then annihilate to produce ultrahigh energy cosmic rays. The neutrinos themselves interact too weakly with nuclei in our atmosphere to produce the observed high altitude air showers, but they can annihilate with CNB neutrinos through the Z-boson resonance to produce “local” photons and protons, with a probability of order $10^{-2\pm 1}$. The resulting Z-boson then decays to produce a shower of hadrons and leptons, a “Z-burst”. The products of the Z decay, as measured at the CERN and SLAC colliders, include on average 20 photons and 2 nucleons. These photons and protons are the candidate particles for initiating the observed trans-GZK air-showers. Because the annihilation process is resonant, the event energy is unique. It is $E_{Z-burst} = 4 \times 10^{21} [m_\nu]^{-1}$ eV in terms of the neutrino mass (in units of eV). Each nucleon and photon in the burst carries on average an energy which is a few percent of the Z-burst energy.

The Z-burst hypothesis based on the assumption that there exists a significant flux of neutrinos at $E \sim 10^{22}$ eV, perhaps from topological defects. Some predictive consequences of this hypothesis are (a) that the direction of the air showers should be close to the directions of their cosmological sources, (b) that there may be multiple events coming from the directions of the strongest sources, (c) that there exists a relationship between the maximum shower energy attainable and the terrestrially-measured neutrino mass, and (d) that there may be an observable large-scale anisotropy caused by a clustering of 2 K neutrinos within the cosmic-ray attenuation distance.

2 NEUTRINO FLUX PREDICTIONS

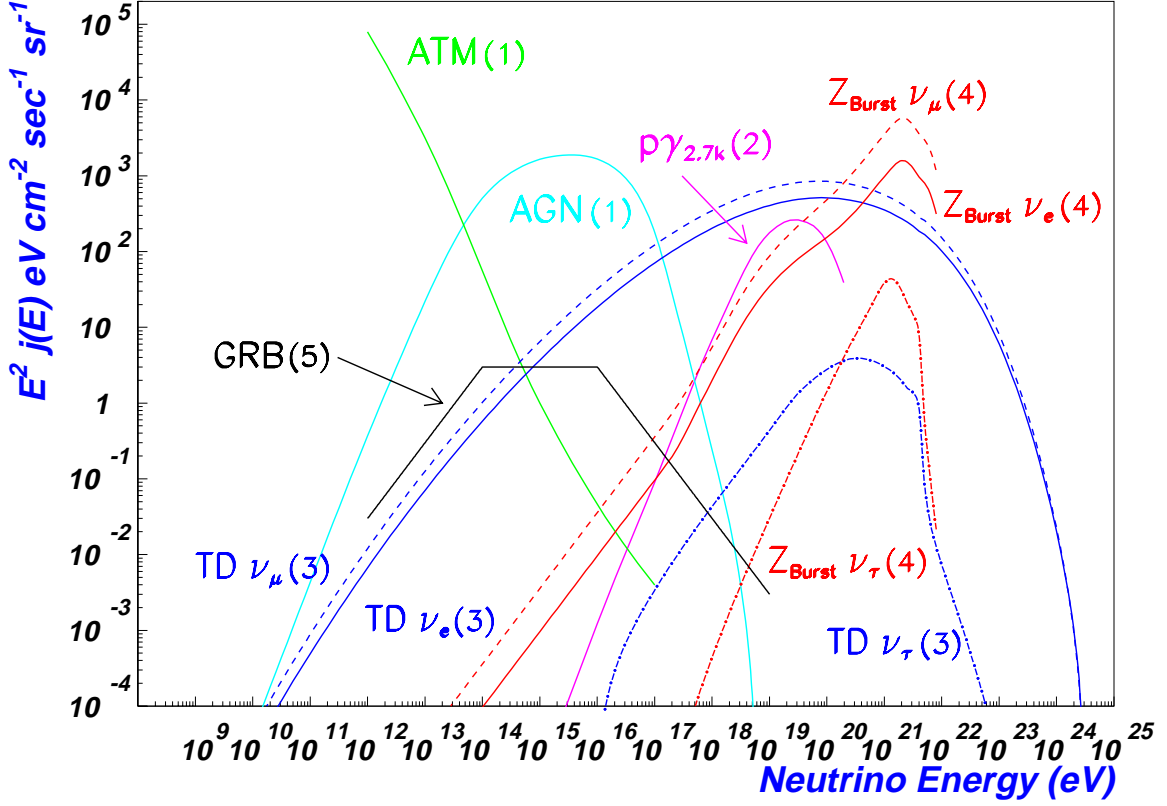


Figure 1: Neutrino flux predictions: Atmospheric and AGN (1: Stecker & Salamon 1996, Space Sci Rev 75, 341), photomeson production via $p\gamma_{2.7K}$ (2: Stecker, Done, Salamon, & Sommers 1991, Phys. Rev. Letters 66, 2697), topological defects (3: Sigl, Lee, Bhattacharjee, & Yoshida 1998, Phys. Rev. D 59, 043504), $m_X = 10^{16}$ GeV, $X \rightarrow q + q$, supersymmetric fragmentation), Z_{Burst} (4: Yoshida, Sigl, & Lee 1998, Phys. Rev. Letters 81, 5055), $m_\nu = 1$ eV, Primary $\Phi_\nu \sim E^{-1}$, and gamma ray bursts (5: Waxman & Bahcall 1997, Phys. Rev. Letters 78, 2292).

Figure 1 illustrates the high energy neutrino flux predictions from various astrophysical sources as a function of neutrino energy. Note that curves show the differential neutrino flux multiplied by E_ν^2 which is equivalent to an energy flux. In the energy range of 10^{14} to 10^{17} eV, the AGN neutrino flux is predicted to dominate over other sources. However, neutrinos from individual gamma-ray bursts may be observable via their directionality and short, intense time characteristics. The time-averaged

background flux from all bursts is shown in the figure. In the energy range $E \geq 10^{18}$ eV, neutrinos are produced from photomeson interactions of ultrahigh energy cosmic rays with the 3 K background photons. The highest energy neutrinos ($E \geq 10^{20}$ eV) are presumed to arise from more the speculative physics of topological defects and Z-bursts.

The proposed high energy neutrinos sources also have different signatures in terms of other observables which include coincidences with other observations (GRB's), anisotropy (Z-burst's), and specific relations to the number of hadronic or photonic air showers also induced by the phenomena (topological defectss, Z-burst's, and 3 K photomeson neutrinos). The distiguishing characteristics of these neutrino sources are summarized in Table 1.

Test	GRB	AGN	TD	Z-Burst	$p\gamma_{2.7K}$
Coincidence with a GRB	X	-	-	-	-
$(N_\nu/N_p) \gg 1$	-	-	X	X	X
$(N_\gamma/N_p) \gg 1$	-	-	X	X	X
Anisotropy	NA	NA	-	X	-
Characterisitic					
Energy	10^{14} eV	10^{15} eV	10^{24} eV	$\frac{10^{20} \text{ eV}}{m_\nu \text{ (eV)}}$	10^{19} eV
Multiple Events	X	X	-	X	-

Table 1: Distinguishing characteristics of the different sources of ultra-high energy neutrinos.

3 EXPERIMENTAL SIGNATURES AND RATES

3.1 Air Fluorescence Events

A space-based experiment viewing 10^6 km² of the surface of the Earth also monitors $\sim 10^{13}$ metric tons of atmosphere. This large target mass opens the possibility

of observing the interactions of ultra-high energy (UHE) neutrinos in this atmospheric volume. The distribution of atmospheric depth of neutrino interactions is approximately uniform due to the extremely long interaction path of neutrinos in the atmosphere. This offers a unique signature of neutrino-induced airshowers as a significant portion of the neutrino interactions will be deep in the atmosphere, i.e. near horizontal, and well separated from airshowers induced by hadrons and photons. A space-based experiment observing the fluorescence signal of airshowers will have a segmented detector plane (pixels) in order to measure the spatial development of the airshowers. Additionally, the signals will be recorded with a very fine time resolution in order to measure the temporal development of the showers. This experimental configuration yields a multiple pixel signature for near horizontal airshowers which translates into straight-forward detection with sufficient angular resolution to guarantee separation of neutrino induced events from the hadronic (or electromagnetic) airshower background.

At ultrahigh energies, the cross sections for neutrino and antineutrino interactions with quarks become equivalent (Ghandhi, *et al.* 1998, Phys Rev D, 58, 093009). The kinematics of UHE neutrino interactions ($E_\nu > 10^9$ GeV) leads to the condition that average energy of the resulting lepton will be approximately 80% of the incident neutrino energy. The remaining 20% will materialize in the form of a hadronic cascade from the neutrino interaction point. Charged current neutrino interactions will, on average, yield an UHE charged lepton and a hadronic airshower. At these energies, electrons will generate electronic airshowers while muons and taus will make airshowers with reduced particle densities and, thus, fluorescence signals. The taus offer an additional, “double-bang” signature because of their lifetime and decay modes. At 10^{10} GeV, $\gamma c\tau = 500$ km for a tau after which the particle will decay inducing a second airshower separated from the first, hadronic airshower at the neutrino interaction point.

As a first step in quantifying the rates of neutrino airshower observation, we will focus on the charged current electron neutrino interaction. These deposit 100% of the incident neutrino energy into an airshower and will yield the highest air fluorescence signal for a given neutrino energy of the possible flavor channels. Preliminary Monte Carlo simulation of an OWL/AirWatch instrument have indicated that charged current electron neutrino interactions can be identified with a neutrino aperture of 20 km²-ster at a threshold energy of 3×10^{10} GeV and this aperture grows with the $E_\nu^{0.363}$ assumed increase in neutrino cross section. Event rates can be obtained by convolving this neutrino aperture with neutrino flux predictions and integrating. Note that the neutrino interaction cross section is included in the definition of neutrino aperture. Assuming a 10% duty cycle of the experiment, Table 2 lists the electron neutrino event rates from several possible UHE neutrino sources: neutrinos from the interaction of UHE protons with the microwave background ($p\gamma_{2.7K}$, Stecker *et al.* 1991,

Phys. Rev. Letters 66, 2697) and the more speculative sources of topological defects (Sigl *et al.* 1999, Phys. Rev. D 59, 043504) and the interaction of UHE massive neutrinos with the 2 K relic neutrino background (Z_{Burst} , Yoshida *et al.* 1998, Phys. Rev. Letters 81, 5505).

	$p\gamma_{2.7K}$	Topological Defects	Z_{Burst}
ν_e Events/Year	5	16	9

Table 2: Anticipated electron neutrino, charged current event rates in a baseline OWL/AirWatch experiment.

3.2 Upward Cherenkov Events

The ensemble of charged particles in an airshower will produce a large photon signal from Cherenkov radiation which is strongly peaked in the forward direction and which is much stronger than the signal due to air fluorescence at a given energy. This translates into a much reduced energy threshold for observing airshowers *via* Cherenkov radiation. As this signal is highly directional, an orbiting instrument will only observe those events where the airshower is moving towards the experiment with the instrument located in the field of the narrow, Cherenkov cone.

Virtually all particles, including neutrinos with $E \geq 40$ TeV, are attenuated by the Earth. However, tau neutrinos will regenerate themselves, albeit at a lower energy, due to the fact that both charged and neutral current interactions will have a tau neutrino in the eventual, final state (see section 1.5). Thus, the use of the Earth as a tau neutrino filter leads to the possibility of a cosmological, long-baseline tau neutrino appearance experiment. Moreover, an experiment which monitors $\sim 10^6$ km² of the Earth's surface samples an incredible target mass of the Earth's crust.

At high energies ($E > 10^6$ GeV), neutrinos and antineutrinos interact with approximately equal cross sections. Furthermore, the average energy in the lepton resulting from a neutrino interaction is greater than 70% of the incident neutrino energy. Tau leptons produced in charged current, neutrino interactions will have a flight path of length $\gamma c\tau$ (≈ 50 m at 10^6 GeV), after which they will decay producing high energy cascades for most of the branching ratio. For interactions in the Earth's crust, those events which occur at a depth less than $\gamma c\tau$ will have a tau coming out of the Earth and generating an airshower. For a target area of 10^6 km², this yields a target mass of $10^8 \times (E_\nu/\text{GeV})$ metric tons, e.g. 10^{14} metric tons at an energy of 10^6 GeV.

Preliminary investigation of the response of an OWL/AirWatch instrument has indicated that the experiment would have a threshold energy $\geq 10^5$ GeV to upward, Cherenkov airshowers. Assuming that the Super-Kamiokande atmospheric neutrino

results are due to $\nu_\mu \rightarrow \nu_\tau$ oscillations, the predicted AGN muon neutrino flux (Stecker & Salamon 1996, Space Sci. Rev. 75, 341) indicates that OWL/AirWatch could observe several hundred tau events per year. Thus OWL/AirWatch would measure the flux of AGN neutrinos and observe their oscillations.

4 Conclusion

An OWL/Airwatch array of satellite-based optics optimized to monitor a significant volume of Earth's atmosphere for the purpose of studying the characteristics of giant atmospheric air showers induced by ultrahigh energy neutrinos (as well as ultrahigh energy cosmic rays) can open a new window of astronomy and physics which will explore the ultrahigh energy neutrino universe.

5 Acknowledgments

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