HIGH ENERGY COSMIC NEUTRINOS

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While the general principles of high-energy neutrino detection have been understood for many years, the deep, remote geographical locations of suitable detector sites have challenged the ingenuity of experimentalists, who have confronted unusual deployment, calibration, and robustness issues. Two high energy neutrino programs are now operating (Baikal and AMANDA), with the expectation of ushering in an era of multi-messenger astronomy, and two Mediterranean programs have made impressive progress. The detectors are optimized to detect neutrinos with energies of the order of 1-10 TeV, although they are capable of detecting neutrinos with energies of tens of MeV to greater than PeV. This paper outlines the interdisciplinary scientific agenda, which span the fields of astronomy, particle physics, and cosmic ray physics, and describes ongoing worldwide experimental programs to realize these goals.

1 Introduction

The high energy frontier has traditionally led to dramatic breakthroughs in our understanding of nature. High energy neutrino detectors are designed to probe of some of the most violent and energetic phenomena in the Universe. Neutrinos born in the hearts of these phenomena provide a unique view of how nature accelerates particles and clarify the role of hadrons in the astrophysical milieu. Once produced, neutrinos are unaffected by intervening matter or photons. Being unchanged, they propagate through the universe undisturbed by magnetic fields. Given the current uncertainty in the location of the sources of extremely energetic cosmic rays, the neutrino messenger may be the only route to clear identification.

Theorists have identified a variety of potential sites of high energy neutrino production, and several extensive reviews of this topic have appeared recently in the literature. For example, Protheroe has summarized the astrophysical predictions of diffuse neutrino intensities between 1 TeV and the GUT scale. Recently, Gamma Ray Bursts (GRBs) have occupied the theoretical spotlight with the discovery that they are distant extragalactic phenomena and therefore the most energetic events observed in the Universe. Waxman and Bahcall have argued that GRBs are the sources of the extremely high energy (EHE) cosmic rays and prodigious sources of high energy neutrinos. The predicted flux is tied to the measured power density of EHE cosmic rays, which also has been used to constrain the neutrino flux in proton blazer models of AGN. Though this procedure is still generating significant debate, there is no doubt that models should not over-produce cosmic rays.

Just as multi-wavelength studies have provided unparalleled insight on many astronomical sources, multi-messenger studies by neutrino, gamma ray, and gravity wave detectors may be the Rosetta stone of cosmic accelerators. For example, the AMANDA neutrino facility, located at the South Pole, contemporaneously observes the same sky as new, powerful gamma ray telescopes in the northern hemisphere. Coincidence experiments can also be contemplated with space-based gamma ray observatories and gravitational wave detectors such as LIGO or VIRGO. At the very highest energies, charged cosmic rays are expected to deviate only slightly from line-of-sight trajectories. Should the Hi Res and Auger Observatories identify sources of extremely energetic particles, then concurrent observations by neutrino telescopes can provide additional information on the local environment of the accelerator.

In all models of particle acceleration to extreme energies, the flux decreases with energy. The decreasing flux is not fully compensated by an increasing sensitivity of the neutrino detector. This leads to a strategy that concentrates on somewhat lower energy neutrinos, acting as surrogates for the extremely energetic, but far rarer, cosmic rays.

The essential characteristics of a neutrino telescope have been known for more than two decades. Markov suggested in 1960 that the ocean would be a suitable site for constructing a large neutrino detector based on the detection of Cherenkov light, and most important features were discussed and specified during a series of workshops devoted to developing the DUMAND concept. Halzen and Learned introduced a twist on the general scheme by promoting polar ice as suitable medium. Until recently, workable implementations of these sensible ideas have been thwarted by unusual technical and logistical challenges associated with the remote deployment of hardware in media that differ from ordinary purified water in several important details. All current architectures for high energy neutrino facilities rely a sparse array of optical sensors within deep ice, ocean or lake waters. The optical sensors respond to the UV dominated cherenkov radiation emitted by neutrino-induced muons or neutrino-induced hadronic and electromagnetic
cascades. Large detector volumes are required because the predicted flux of cosmic neutrinos and the known interaction probabilities at the energies of interest are relatively small. The detection probability, defined as the ratio between the range of the muon to the interaction mean free path of the neutrino, is only $10^{-3}$ for a $\nu_\mu$ with an energy of 1 TeV. Moreover, the rare signal events must be extracted from a large flux of atmospheric muon background. For example, at sea level the number of background muons per unit area exceeds the expected neutrino-induced muon signal by $\sim 10^{11}$, so neutrino detectors are constructed at large depths to reduce this unwanted signal. Even at depths of 2 km of water equivalent, down-going background exceeds predicted signal by a factor of $\sim 10^6$. The combination of large volume, large overburden, and desire to minimize material costs leaves experimentalists with few options other than to construct a detector within a remote, naturally occurring, transparent medium such as ice or water (no excavated caves or mines are large enough). The formidable technical challenge of remote operation distinguishes high energy neutrino facilities from existing solar and accelerator-based neutrino detectors. It is one factor which has spurred the development of surface detectors (e.g., GRANDE and HANUL\textsuperscript{14}) despite the daunting background difficulties.

Cherenkov techniques are now well understood and illustrated below (see Fig. 1). A high energy neutrino a degree, if the energy is greater than 1 TeV. The angular correlation between charged lepton and neutrino improves as the $1/\sqrt{E}$, so eventually multiple coulomb scattering becomes the dominate factor in the angular resolution. Conceivably, neutrino directions can be located to $\sim 0.1^\circ$ in some designs\textsuperscript{15}. Source localization can be improved by the detection of multiple events, but unless the event rate is unexpectedly large, the angular resolution is not competitive with conventional astronomy. Therefore sources must be identified statistically - by searching for a class of objects that lie within the angular error boxes. Confidence will be bolstered if theoretical models of that class of objects are consistent with high energy neutrino production. The relatively limited number of potential sites of high energy neutrino production suggests that source confusion is unlikely to be a problem.

The muon is detected by distributing photon sensors (large diameter photomultiplier tubes - PMTs) over the largest possible volume of transparent medium and recording the arrival times and intensity of the Cherenkov wavefront. Accurate reconstruction relies on actively tracking events over linear dimensions exceeding tens of meters and measuring the arrival of the Cherenkov wavefront to tens of nanoseconds or better. Geometries of the arrays are optimized according to the optical properties of the detector media — those media that generate less precision in the arrival time of the Cherenkov wavefront can be compensated by larger detectors with greater average pathlength. Instrumented volume can be increased by utilizing a medium with a large optical attenuation length. Naturally, volumes increase with additional sensors, so per unit cost becomes an important design factor.

Muons from neutrino interactions are distinguished from the vastly more numerous atmospheric muons by direction: upward-traveling muons (through the detector) can only originate from nearby neutrino interactions. The earth filters out all other known particles. Great care must be taken to reject the "down-going" atmospheric muons. In practice, muons are properly reconstructed if they traverse typically $\sim 100m$ of pathlength within the boundaries of array defined by the outermost strings, although dense arrays have demonstrated good reconstruction with shorter tracks. Complications arise from the lack of fixed fiducial volume, the presence of events containing multiple muons, decaying muons in flight, and fluctuations in the generation of Cherenkov photons resulting from high energy physics processes. Muon trajectories can pass near enough to trigger the array, but too far outside the detector boundary for proper reconstruction.

Reconstruction is tied to specific assumptions about the event topology. For example, the usual assumptions

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**Figure 1:** Muon trajectories can be reconstructed by timing the passage of the Cherenkov wavefront. The numbers indicate the time sequence of the arrival of the photons.
for a neutrino-induced muon event are: 1) only one particle, 2) uniformly ionizing, 3) travels at the speed of light, and 4) traverses the entire detector. Deviation from these assumptions, such as stopping muons or decays in flight, multiple-muon events, or muon-bremsstrahlung result in poorer reconstruction. Once the event is reconstructed, selection criteria must be established that reject events that are likely to be poorly reconstructed while maintaining good efficiency for signal events.

Neutrino-induced electrons produce electromagnetic cascades that generate very bright, localized bursts of Cherenkov photons. While the directional information is poor compared to muon tracks, the energy resolution is far superior. In media with moderate scattering, the sensors nearest the cascade vertex provide the directional information, while distant sensors sample from an expanding diffusive wavefront to provide a calorimetric measurement. The spherical topology of the cascade events readily distinguish them from the most common atmospheric muon backgrounds. Therefore, muon-induced bremsstrahlung and pair production become the dominant background. In this sense, the techniques of detecting muon-neutrinos and electron neutrinos are complementary. The good angular precision and superior sensitivity of muon detection is traded for improved energy resolution and lower background rates. At energies above 1 TeV, the irreducible flux of atmospheric $\nu_\mu$ is less than $\nu_\nu$, because fewer atmospheric muons decay before reaching the detector as the muon energy increases.

As mentioned, the dominant source of background in high energy neutrino detectors is downward muon tracks generated by cosmic ray interactions in the atmosphere. This background can be avoided by constructing a detector at $\geq 10$ kmw (kilometers of water equivalent) depths, but such depths are logistically impossible to attain. Rather, large volume detectors are constructed at intermediate depths, and the background must be removed by other methods. In principle, the angular direction distinguishes astrophysical neutrino signals from the background of atmospheric muons - muons originating from below the horizon must originate from neutrino interaction. However, errors in the reconstructed direction of muon trajectory can result in misinterpreting down-going muons as upward going muons. For detector sites at depths between 1 and 4 kmw, and energy thresholds of $\sim 10$ GeV, the rate of down-going muons exceed potential signal rates by factors of $10^8 - 10^9$ (assuming atmospheric neutrinos as signal). Therefore, an important design specification involves the rejection factor, $R$, defined as $A_{eff}(signal)/A_{eff}(mis)$, where $A_{eff}(mis) = F_m \times A_{eff}(\mu_{atm})$, $A_{eff}(\mu_{atm})$ is the effective area for the detection of down-going muons, and $F_m$ is the fraction of down-going muons misidentified as upward going. The rejection factor must be greater than $10^8$ for the best case conditions. In the simplest description, $F_m$ is a constant, but it may be treated as an angular dependent scattering probability $P(\theta, \theta')$ in more complex descriptions. As the energy threshold of the detector is increased to $\sim 10^{15}$ eV, the ratio of downgoing atmospheric muons to expected signal decreases, reaching unity in the vicinity of 1 PeV. Since the required level of rejection is less at higher energy thresholds, event selection criteria can be optimized to achieve much larger effective areas than could be achieved with larger rejection requirements. Detection methods with sufficient energy resolution to identify PeV events can be used to search the entire sky. Simulations show that the energy of $\nu_\mu$-induced cascades may be measured with sufficient accuracy, assuming the vertex is contained within the volume of the array. The quoted values in the literature for effective detection area cause much confusion because they are a function of lepton energy, zenith angle, and required rejection factor which differs between physics objectives. The effective volume becomes useful when the range of the muon is comparable to the largest dimension of the array. For muon detection at medium energies (and for all cascade events), the effective volume becomes a convenient parameter of detector sensitivity, but it too depends on energy and rejection factor.

Atmospheric neutrinos form an irreducible background in the sense that they cannot be differentiated from non-terrestrial neutrino signals on an event by event basis. Since the energy spectra and angular distributions of atmospheric neutrinos are reasonably well known from measurement and calculation, statistical techniques using energy spectra, spatial and temporal correlations, etc. can confirm or reject a hypothesis involving atmospheric neutrinos.

The multifaceted scientific objectives of high energy neutrino telescopes are distributed across the fields of cosmic ray physics, astronomy, and particle physics. This diversity emphasizes the interdisciplinary potential of these detectors. Two high energy neutrino programs are now operating (Baikal and AMANDA) and two Mediterranean programs have made impressive progress. Neutrino observatories are optimized to detect neutrinos with energies of the order of 1-10 TeV, although they are capable of detecting neutrinos with energies of tens of MeV to greater than PeV. These detectors are distinguished by the broad range in energy response.

2 Science Goals

The scientific agenda is too broad to be covered within the limited space of this paper, so I discuss only a few examples. Readers interested in greater detail should consult the reviews referenced in the introduction. The physics goals can be categorized according to the energy
of the neutrino: low (~$10^6$eV), medium (10-100 GeV), and high (≥1 TeV). A transient burst of low energy neutrino emission from Supernova explosions or Gamma Ray Bursts (GRBs) can be detected by summing the random noise signals from the photomultiplier tubes in the optical modules within the array. A supernova burst would manifest itself as a statistically significant increase in the summed signal due to the excess photons generated by the low energy neutrino interactions. Sensitivity to transient events is improved by embedding the array in an environment such as polar ice, where the random noise level is low because the internally generated noise of the photomultiplier tube is reduced at cold temperatures and the externally generated background light from radioactive impurities is negligible. The AMANDA collaboration agreed to join the Supernova Early Alert Network to confirm galactic supernova and determine the direction by triangulation of the neutrino wavefront, which can precede the photon signal by several hours or more. The polar location of AMANDA simplifies the task of triangulation, but the angular resolution achieved by the SuperKamiokande experiment may be superior. Neutrino observatories could search for nearby extragalactic bursts by improving the collection area of the optical sensors, implementing techniques to reduce the intrinsic noise, and increasing the number of sensors in the array beyond several thousand.

The recently reported evidence for neutrino oscillation in the atmospheric neutrino data has triggered the neutrino telescope community to investigate the physics capabilities of their detectors for this particular science objective. The energy spectrum of atmospheric neutrinos (hashed box, Fig. 2 – taken from Protheroe’s review paper (ref. 12)) is a steep power law, suggesting that the detected events will be predominantly medium energy and the rate will be influenced by the energy threshold. Therefore, using atmospheric neutrinos to search for neutrino oscillation requires energy thresholds of 5-20 GeV. Detectors, such as Baikal NT-200 and NESTOR, or the insertion of high density strings into the AMANDA-II array, are designed to achieve this goal.

Atmospheric neutrinos may reveal neutrino oscillations in several ways. A deviation from the expected angular distribution would be strong evidence for oscillations. Neutrino detectors can contribute to this science by virtue of their large detection area and consequent increase in statistical significance. Unfortunately, these are difficult measurements for neutrino arrays. For the simplest case of two oscillating neutrino species, the probability that a neutrino $\nu$ of flavor $i(e, \mu, \tau)$ will oscillate into a different flavor $x$ is given by

$$P(\nu_i \to \nu_x) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/(E_n GeV))$$

where $\theta$ is the mixing angle, $\Delta m^2$ is the difference in mass squared in eV$^2$ of the two mass eigenstates, $L$ is pathlength between generating vertex and detector, and $E_n$ is the energy of the neutrino.

Unless the neutrino-induced muon event is completely contained within the detector, the neutrino energy is not well measured. For the current generation of neutrino detectors, through-going upward muons are the most likely detection mode, but this only establishes a lower limit on the neutrino energy. Moreover, the energy threshold for muons which traverse the array is relatively high, so as $E_n$ increases, angular deviations become very subtle. For parameters of $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and maximal mixing, the angular and energy dependence of the detector area must be determined to 5% or better. It remains to be seen if this accuracy can be achieved in practice. Also $\nu_e$ events must be differentiated from $\nu_\mu$ events.

A second idea takes advantage of the particular strengths of the existing neutrino arrays. The linear symmetry of string-based designs results in excellent sensitivity to nearly vertical tracks. The long lengths of instrumentation can contain neutrino-induced events over a large interval of energies. By concentrating on nearly vertical tracks, backgrounds are easier to reject. The small vertical spacing of optical sensors (compared to the horizontal spacing of the strings) reduce the energy threshold to interesting levels. The detection efficiency as a function of energy can be calculated more accurately than for the entire hemisphere. In addition, the AMANDA array can calibrate its vertical sensitivity with a well defined muon beam using coincidence events that simultaneously trigger another array at 900 meters. If the vertex is contained within the central part of the array, then the light from the interaction vertex and outgoing muon can be
modeled to establish the energy of the neutrino with sufficient accuracy. Obviously, the event rates are much lower for a restricted solid angle, but the large detection area results in sufficient statistics. However, the same concern about being able to differentiate $\nu_e$ and $\nu_\mu$ events applies to this technique.

A third method to search for neutrino oscillation over long pathlengths (or baselines) utilize existing accelerators to direct a beam of $\nu_\mu$ particles with a known energy spectrum toward large neutrino telescopes located at distances between 1000 and 10000 km. While most discussion has involved CERN and planned neutrino telescopes in the Mediterranean, the idea works the same for any accelerator and neutrino observatory as long as a neutrino beam can be pointed in the right direction.

For kilometer-scale detectors, a significant fraction of neutrino-induced muons will be contained within the actively instrumented volume, so a calorimetric measurement of the neutrino energy is possible. However, the larger spacing between sensors results in higher energy thresholds which may be above the energies of interest. Medium energy physics objectives can be retained if the kilometer-scale array surrounds a first generation neutrino array. The composite detector can identify and reject atmospheric muons, reducing background rejection requirements in the denser central region of the composite array.

Neutrinos may be emitted from the center of the sun or earth as a consequence of the annihilation of weakly-interacting cold dark matter particles (WIMPs) that accumulate at the centers of these objects. Galactic WIMPs, scattering off nuclei, lose energy and may become gravitationally trapped. One interesting class of WIMP candidates arise from minimal supersymmetric (SUSY) theory. Within this framework, Bergstrom et al. have calculated the discovery potential for neutrino observatories and beautifully illustrate their power to complement other search methods. Apparently, the parameterized ignorance of SUSY models is too vast to be completely constrained by a single search technique. Bergstrom et al. have attacked this worrisome deficiency by combining the limits from cosmic ray antiproton instruments with the anticipated sensitivity of gamma ray satellites and neutrino observatories. A comprehensive search strategy for SUSY particles benefits enormously from the complementary information provided by neutrino telescopes. Combining astrophysical data from special purpose and multipurpose survey instruments creates an intriguing blueprint for future search strategies.

The primary motivation for very large neutrino telescopes is to identify galactic or extragalactic sources, which may be point-like or diffuse. The high energy frontier holds the most promise to achieve this scientific priority. The atmospheric neutrino and muon backgrounds are lower, the effective area of the detector is larger, and angular resolution is likely to be better. Detection of diffuse sources requires good energy resolution with well understood tails but only marginal angular resolution.

Theoretical activity has centered on modeling two classes of objects: galaxies with active nuclei, or AGNs, and gamma ray bursts (GRBs). These objects are known to emit high energy photons, and may also be the accelerators of the highest energy cosmic rays. At TeV energies, the luminosities of some AGN are observed to flare by an order of magnitude in about a day, suggesting very compact central engines. Models of the acceleration mechanism within AGN differ ingeniously. The intensity of neutrino emission ranges from negligible in models that rely solely on electron acceleration to detectable in the most optimistic models based on hadron acceleration. Neutrino observatories are likely to play a key role in settling the debate.

If hadronic acceleration is present in AGN, then a diffuse glow of neutrino emission should be observed uniformly over the sky, originating from distant (and more powerful) AGN. Fig. 2 shows the energy spectrum for a representative sample of neutrino models.

Figure 3, also taken from Protheroe, converts the neutrino intensity predictions into an event rate for a detector with an effective area of 0.1 km$^2$. The calculations include absorption by the earth, which becomes important for energies $\geq$100 TeV$^4$. Diffuse sources could be distinguished from atmospheric neutrino background by a flattening energy spectrum above 100 TeV. Some models can be differentiated by their cutoff at the highest energies and spectral shape. Excellent energy resolution will be necessary to select events with high energies and eliminate the lower energy atmospheric neutrino background. The representative models show that there is little reduction in signal until the energy threshold exceeds 10-100 TeV, with the exception of the atmospheric neutrino signal. Theoretical considerations place a premium on detectors which attain excellent performance at high energies.

A few caveats should be kept in mind when interpreting the previous figures. (1) The only "background" shown in Fig. 2 and 3 is atmospheric neutrinos, but the rejection of down-going atmospheric muons represents a non-trivial hurdle that must be surmounted. (2) Point sources can be located to within a small fraction of a steradian, and the atmospheric neutrino background decreases accordingly. Signal significance increases as $\sim \sqrt{A_{eff}/\delta(\theta)}$, where $\delta(\theta)$ is the angular extent of the source (or if considering a point source, proportional to the angular resolution of the detector.) (3) Correlated photon observations of GRBs by BATSE provide a special opportunity. Events rates are determined by integrating over all GRB events, and predicted to be
Horizontal air shower techniques can be employed to explore the neutrino sky at extremely high energies. Conceivably, with ~10 km$^2$ of water equivalent target volume for $E_{\nu} > 10^{19}$ eV, the Auger air shower array will have the sensitivity to search for neutrinos from cosmic ray interactions with the cosmic microwave background and more speculative signals from topological defects.

Obviously, the desire to understand the optical and physical properties of the local environment create many interdisciplinary opportunities. Underwater neutrino observatories provide the facilities to monitor the time variability of bioluminescence, temperature, salinity, water currents, biofouling, etc. The NESTOR collaboration has secured funding to deploy an optical cable from shore to site of Pylos instrumented with sensors of interest to oceanographers and neutrino physicists. Multidisciplinary opportunities in Antarctic ice led to the proposal to establish the Deep Ice Science and Technology Center (STC). For example, DeepIce STC will promote interactions between seismologists and neutrino physicists to construct a large seismic array for tomographic studies of the earth's interior. The Baikal detector monitors the seasonal water exchange processes in this unique Siberian lake.

3 High Energy Neutrino Observatories

The visionary decision by the DUMAND collaboration over 25 years ago to construct a large telescope nearly 5000 m under the ocean and 40 km from shore launched the experimental effort to construct a neutrino observatory. The design goals then were much the same as they are now: threshold energy for neutrino detection $\sim 10 - 100$ GeV, effective detection area = 20,000 m$^2$, number of optical sensors = 200. Unfortunately, this pioneering effort fell victim to expensive logistical difficulties and was de-funded.

At present, four groups are competing in the construction of high energy neutrino observatories: two in the Mediterranean – NESTOR and ANTARES – one in Lake Baikal, Siberia, called NT-200 and – and one in deep ice at the South Pole called AMANDA. Baikal’s NT-200 and AMANDA are currently in operation, and feasibility studies are being carried out at the Mediterranean sites. The geographical location is shown in Fig. 4.

AMANDA anchors the effort in the southern hemisphere and complements the sky coverage of the Siberian and planned Mediterranean observatories. Several new concepts for surface neutrino observatories are being discussed, but I will not cover those ideas here.

The Baikal collaboration has been accumulating experience with the construction and operation of water-based neutrino observatories since 1993, the longest track...
record of any group. Those initial efforts were followed by intermediate stages of construction that include configurations with 96 and 144 optical sensors and culminate with NT-200, which was completed in April 1998. It consists of 192 optical sensors positioned at a depth of 1.1 km below the surface of the lake. The sensors are arranged in pairs and operated in coincidence to suppress unrelated signals from bioluminescence and internally generated random noise. Deployment, the "Achilles Heel" of remotely located neutrino observatories, has been solved by utilizing the seasonal ice cover on Lake Baikal. The solid platform can be accessed for significant periods of time, enabling reliable detector assembly and repair of detector elements.

An umbrella-like frame maintains eight vertical strings of optical sensors, consisting of a glass pressure vessel and a photomultiplier tube (PMT) with a diameter of 37 cm. The operation and performance of the Baikal detector is understood. They have shown that the optical properties of the water medium and 1.1 km depth are adequate to measure the angular spectrum of atmospheric muons with good accuracy and to identify atmospheric neutrinos with the 96 element array (see Fig. 5). This result bodes well for the Mediterranean sites because they are deeper and their optical properties are better. Neutrino events were extracted from 70 days of livetime. After reconstruction, neutrino events were selected by imposing a restriction on the chi-square of the fit and requiring consistency between the reconstructed trajectory and the locations of sensors registering photons. In this context, sensors that do not register photons carry important information as well. Finally, the non-gaussian tails of the angular distribution were reduced by imposing the condition that events must traverse more than 35m within the array.

The high PMT density of the NT-200 design results in a low energy threshold - advantageous for medium energy science goals - but limits the effective area at high energies to $\sim 5 \times 10^3 m^2$, presumably too small to detect neutrinos from non-terrestrial sources. A strawman design for a 2000 sensor array has been presented. The effective area would be $\sim 10^5 m^2$, while retaining a 10-20 GeV energy threshold. It could fill the niche between current generation of neutrino detectors and future kilometer-scale arrays with, presumably, much higher energy thresholds.

A flurry of research and development activities have occupied the NESTOR and ANTARES collaborations as they assess the relevant physical and optical parameters of their sites. Deployment methods are being developed and refined through a series of operations using barges, research and military vessels. The NESTOR and ANTARES groups envision quite different deployment schemes, array designs, and signal processing. Technological solutions are being sought which are affordable, reliable, and expandable.

Over the past few years, the ANTARES collaboration has methodically determined the critical optical parameters of a 2400m deep site off the coast of Toulon, France. Significant R&D has concentrated on string deployment and retrieval. They have reported that one string has been installed at the site and recovered after one year of flawless operation. This success paves the way for more complex and difficult operations, such as the deployment of a fully functional string of sensors, deployment of multiple strings, or the insertion of a string within an existing array.

Precision attenuation (Fig. 6) and scattering measurements at wavelength of 450nm are extremely encour-
Determination of $\Lambda_{\text{attenuation}}$

\[ D^2 \Omega_{\text{LED}} \]

$\Lambda_{\text{attenuation}}$

$41 \pm 1_{\text{stat}} \pm 1_{\text{sys}} \text{ m}$

- Measurement in water
- Calibration in air

Distance (m)

Figure 6: Attenuation length for water at ANTARES site (at 450nm).

down-going atmospheric muons, but places greater stress on the penetrator connections. Hexagonal floors, rather than strings, comprise the basic unit. The array consists of 12 floors, fixed in place with an extensive network of wire guides, and assembled to form a 200m tall tower. Site testing is complete, showing excellent optical properties. Like the Baikal design, a symmetric up-down arrangement of PMT orientations will insure better uniformity in its angular acceptance. Upward facing PMTs are thought not to suffer from obscuration due to sedimentation or biological growth. The array design is expected to achieve low energy threshold due to the relatively high density of optical sensors. Horizontal separations between optical modules on a given floor are slightly larger than 30 meters. Recently, the NESTOR collaboration has performed mechanical tests by successfully towing a single floor out to sea and deploying to a depth of 2600 m. In the near future, a far more ambitious plan to deploy two, fully instrumented, floors to depth. It is hoped that these tests will establish the electro-mechanical durability of the signal processing and transmission systems.

AMANDA was completed in early 1997 and has operated reliably since. The rapid growth of the AMANDA program makes it a strong candidate for expansion to kilometer scales. From its inception, AMANDA has been designed to confront the robustness issue, which has been the primary technological difficulty of water based arrays. Three months of access to a solid platform ensures that sufficient time is available for certification and quality assurance assessment. The infrastructure at the South Pole, soon to be expanded and modernized, provides a reliable transportation system, communications, adequate power, laboratory facilities, and the resources to solve unexpected difficulties in real time. The distance between the optical sensors and the surface facilities is only a few kilometers, so a highly redundant array architecture could be implemented with no potential single-point catastrophes. It also accommodates a modest failure rate of individual sensors. The architecture permits both analog and digital signal processing solutions. A conservative approach to the in situ hardware was adopted. Given the geographic novelty of the South Pole site, a simple, but mechanically and electrically robust design based on analog transmission through copper cables was implemented. Experience from time-of-flight detectors indicated that adequate timing resolution could be achieved despite the signal dispersion in the long cables. High gain PMTs were developed to compensate for the large cable dispersion and attenuation. The extraordinary thermal stability of the ice suggested a very low rate of drift in the calibrated parameters, which in turn simplified manpower requirements. Unlike water, ice was recognized to present few long term electrical problems.

aging. The deliberate development plan calls for the construction of a demonstration array, consisting of 100-200 optical sensors, by the end of 1999 (although the configuration and schedule are subject to change).

Environmental studies at the Toulon site show that upward facing PMTs lose sensitivity over time due to the accumulation of organic debris, so the ANTARES design consists of only downward looking PMTs. Deep sea currents have been measured over a period of a year and show no unusual excursions from expected values.

Simulations of an array consisting of 15 triads of strings (~1000 PMTs) indicate that neutrino events can be clearly identified. Random noise exceeding 50 kHz per optical sensor has been measured, but can be eliminated by straightforward coincidence requirements between neighboring elements in the array. Bioluminescent flashes do not affect local coincidence rates due to the relatively weak intensity of the output and the relatively long duration of the burst. Muon directions should be identified with sub-degree angular resolution.

NESTOR plans to deploy an array of 168 optical sensors at a depth of 3.5-4.0 km of the cost of Pylos, Greece. The large depth significantly reduces the background of
and durability of the PMTs benefitted from the stable, sub-zero, ambient temperatures.

Several unusual obstacles confronted the AMANDA program. The architecture had to accommodate a large uncertainty in the optical properties of polar ice, which were poorly known prior to the initiation of the AMANDA campaign, and in hindsight, overly naive. Nevertheless, the AMANDA collaboration has shown that Antarctic ice is a suitable medium for a neutrino observatory. Remarkably, absorption in Antarctic ice is far better than expected from laboratory measurements. However, the transition depth to bubble-free ice at the South Pole was initially under-estimated\textsuperscript{26}, and the magnitude of the residual scattering in the bubble-free region had to be determined experimentally. Models of the ice structure were greatly improved with the initial data from 800-1000m\textsuperscript{30}. While the transition to bubble-free ice was never in doubt - it being firmly established by deep ice-cores from Greenland and Antarctica - the depth of the transition was reliably bounded by the new models. With the deployment of the first four strings of AMANDA-B, the bubble-free transition was confirmed and fell within the predicted range. Models of the ice could also bound absorption and scattering lengths, but the uncertainties in the model parameters were large. By measuring the the timing distribution of pulses of laser light as a function of wavelength and depth\textsuperscript{31} the optical properties were measured with the the necessary precision. The experiments required that the geometry of the array, timing parameters, and optical properties had to be measured in situ. To complicate matters, the determination of the geometry and optical properties were inter-dependent, so an iterative method of data analysis was developed to address this feature. Fortunately, once the geometry and ice properties are known, they do not change.

Throughout the development of AMANDA, riskier but more capable technologies have been investigated. A rigorous, deliberate evaluation process was instituted which required that laboratory prototypes be installed in-situ and integrated into the existing array to assess reliability, deployment, logistic, and system capability issues. Old and new technologies were combined into hybrid modules, retaining the reliability of the previous methods while evaluating the newer ones. Reliable baseline technologies have been phased out as confidence in the new technologies grew. Both analog and digital technologies are realistic options for signal transmission. Analog technologies, based on laser diode transmitters and optical fibers, offer many advances over the current baseline, including excellent signal fidelity, improved dynamic range, low cross-talk, simplified calibration and debugging. Digital solutions are being explored as well. Full waveform digitization within the module insures that the event contains maximum information. Multiplexing of several sensors on a single cable, not easily implemented in analog transmission, can reduce costs assuming the reliability justifies this cost reduction. Fiber optic cables, one of the big ticket items in the AMANDA-II design, can be eliminated in the digital architecture.

The status of the AMANDA project can be summarized as follows:

- Construction of the first generation AMANDA detector\textsuperscript{2} was completed in the austral summer 96-97. It consists of 302 optical modules, located on 10 separate strings, deployed to depths between 1500-2000 m; see Fig. 7. An optical module (OM) consists of an 8 inch photomultiplier tube (R5912-02) encapsulated in a glass pressure sphere and mounting hardware. Analog signals are sent to the surface via electrical cables in AMANDA-B10. The conservative design has resulted in an in-situ failure rate of only 3%.

- Data taken with the first 4 strings (a total of 80 OM's), deployed in January of 1996 to assess the optical properties of the deep ice, have been analyzed. This partial detector will be referred to as AMANDA-B4. Nearly vertical up-going muons are found at a rate that is statistically consistent with the expected flux of atmospheric neutrinos. As Fig. 8 shows, events are clearly separated from the background population\textsuperscript{5} of poorly reconstructed down-going muons. Simulations and data agree - from a crude check of hardware trigger rate to careful examination of the muon angular distributions as the selection criteria are refined. Starting with $10^5$ events which pass the trigger, a set of selection criteria were sequentially implemented to reduce the number of events misconstructed as upward going. Selection criteria were improved until no events remain in the up-going direction. Absolute event rates agree to within a factor of 3 at all stages of this analysis, limiting the absolute error in the Monte Carlo estimates of effective area.

- The commissioning phase of the full detector is now completed (July '98) and analysis of data from 1997 is in progress. Final calibration of array geometry, cable-dependent time delays, and PMT performance was completed after the return of the first year of full operation. First look analysis indicates that events can be extracted with trajectories in the upward direction. A more extensive evaluation of background and detector performance is currently in progress.

AMANDA-II is an approved and funded expansion of the AMANDA-B array. The proposed array consists
AMANDA as of 1998

Eiffel Tower as comparison (true scaling)

zoomed in on

AMANDA-A (top)

AMANDA-B10 (bottom)

zoomed in on one optical module (OM)

Figure 7: Configuration of Antarctic Muon And Neutrino Detector Array (AMANDA) in 1998.
of 11 additional strings of OMs arranged concentrically around AMANDA-B10. Current simulations predict that AMANDA-II will have an effective detection area of \(\sim 3 \times 10^4 \text{m}^2\) (depending on energy; significantly less for atmospheric neutrinos and somewhat larger for PeV-scale neutrinos) and angular resolution of \(\sim 1^\circ\) (again, depending slightly on energy). Construction of the AMANDA-II upgrade began in January 1998 with the deployment of three strings to a depth of 2350m. Each string contained 42 OMs that were positioned along the lowest kilometer of cable. Thus, these strings serve as a full-scale prototype for a planned expansion to a kilometer-scale array of sensors called IceCube.

The deployment of AMANDA-II strings in 1998 addressed both science and R&D goals. First, the optical properties of the ice at depths above and below AMANDA-B10 were measured. These results will be used to optimize the depth and spacing of the remaining eight strings of AMANDA-II sensors. Second, the longer lever arms of the new strings provides crucial data to verify simulation results on event topologies not readily obtained by AMANDA-B10.

A pair of TV cameras were lowered into the last hole. The resulting images visually confirm the exceptional clarity of the ice deduced from calibration measurements. The fidelity of signal transmission was dramatically improved by transmitting analog signals from the PMT to the surface over optical fiber and electrical cable simultaneously. Optical transmission of signals, using an LED, eliminates the distortion of the PMT waveform while preserving many aspects of the conservative design features introduced by analog signal transmission over electrical cable. The high fidelity of signal reproduction at the surface improves the double-pulse resolution by an order of magnitude. Reconstruction should benefit from better identification of multiphoton signals, and from reduced cross-talk. Time-delay calibration procedures are simplified so fewer manpower resources are required.

The robustness of the optical fiber cables and connectors was improved. One combination of fiber and connector technologies produced a 90% survival rate. Based on the success of the hybrid optical technologies, the remaining AMANDA-II OMs will transmit analog optical and electrical signals to the surface.

Data from the first phase of construction, AMANDA-B4, has been used to measure the optical quality of ice, geometric spacing in situ, and angular distributions of atmospheric muons. During the six month commissioning phase following the first year of AMANDA-B10 operation, system calibration of the array geometry, propagation constants, and gain drifts was completed. Concurrently, software was developed to reduce the 0.5 TB of data by a factor of 10 by filtering events that were readily identified as atmospheric muons.

With logistics, deployment, calibration, and durability issues solved, the AMANDA collaboration focussed its efforts on data analysis by concentrating on the known atmospheric neutrino signal. Although the current AMANDA design is optimized to search for higher energy neutrinos, a sufficient number of atmospheric neutrinos can be observed to verify critical performance parameters at medium energy. The collaboration is developing suitable estimates of energy for both the muon and cascade events. The measured energy spectra can help to distinguish between many potential sources of high energy neutrinos.

Initial analyses have produced upward-going muon events which possess several important topological features that are consistent with atmospheric neutrinos and inconsistent with background. Fig. 9 shows one example of this type of event. Optical modules which detect Cherenkov light are color coded according to the rainbow with the earliest hits in red and latest in blue. The morphology of the detected light is consistent with an up-
ward traveling muon, and inconsistent with timing and morphological characteristics of ~ 20 million simulated background events.

At this early stage of analysis, the reconstruction techniques and selection criteria are continuously being refined so improvements are expected. While AMANDA is capable of detecting a sufficient number of atmospheric neutrinos to verify detector operation, the event rates are low due to the soft energy energy spectrum and the strong background rejection criteria required to identify a diffuse source. As more data is analyzed and efficiencies improve, the comparison of the angular distributions generated by simulation and data will provide a stringent test of the atmospheric neutrino hypothesis.

Searches for steady-state point sources require selection criteria that are optimized for high energy signals. At $\geq$TeV energies, background rejection is aided by angular correlations with known gamma (GeV-TeV) sources. In addition, larger energy thresholds can be imposed during the analysis because the average light output of the muon above $\sim 1$TeV depends linearly on the energy, although the output is highly stochastic which limits the energy resolution. This situation will improve as the neutrino facilities increase in scale and become more symmetric.

4 Future Arrays with Kilometer Dimensions

It may not be strictly accidental that deployment methods based on solid surfaces have enjoyed greater success at this moment, but there is little doubt that deep water deployment can be done. In the long term, they will be challenged to demonstrate that reliability and cost issues remain competitive with AMANDA and NT-200. While the current generation of neutrino observatories represent remarkable achievements, they are only a fraction of the size ultimately required to probe the hadronic sky. In fact, all current programs have the potential for expansion to kilometer scales - it is one of the important design requirements of the current generation of neutrino detectors. Several arguments have been used to coalesce around a detector with kilometer dimensions. A survey of theoretical models of GRB and AGN emission produce general agreement at fluxes that would be detectable with kilometer scale detectors with orders of magnitude bracketing the maximum and minimum fluxes. Given the current state of theoretical uncertainty, the bigger the detector, the better the chances. More persuasively, the symmetric shape and larger volumes offer significant experimental advantages: particle trajectories are reconstructed with much higher efficiency, down-going atmospheric muon background will be simpler to reject, and energy resolution will be improved, perhaps dramatically. It may be possible to distinguish each of the three known neutrino flavors.

Several workshops have been held worldwide to discuss ideas for future expansion of the neutrino observatories. At UC-Irvine, for example, a workshop was held in March 1998 to initiate the conceptual design of the IceCube Neutrino Facility in Antarctica. Scientific goals and priorities were actively debated, and the sensitivity of several strawman designs were studied within the rough constraints of 5000 OMs and fewer than 80 strings. A reasonable estimate of cost, scaling from the default analog-based technology, is $7000 per optical sensor. Deployment and logistics costs must also be accounted for. The construction of IceCube may be completed in 5 years given a reasonable projection of the drilling capacity. The Baikal collaboration envisions an expansion to 2000 OMs. Similarly, the NESTOR and ANTARES groups anticipate significant expansion after successful operation of the first generation detectors.

5 Conclusions

The late Fred Reines, Nobel Laureate and father of neutrino physics, was fond of saying that one should choose to work on physics topics worthy of a lifetime's study. The broad diversity of scientific capabilities and enormous potential of high energy neutrino astrophysics certainly qualifies. In view of the large number of possible sources discussed by theorists and even larger variation in their predicted intensity of neutrino emission, it is plausible that some will be detected by current, or soon-to-be upgraded, neutrino detectors such as AMANDA-II. If history is a guide, there will be surprises as well as these detectors begin to survey the great canvas of the unknown.

High energy neutrino facilities are developing during an era of exciting discoveries in related areas of particle astrophysics: the detection of rapidly varying multi-TeV gamma ray signals from AGN, the discovery that GRBs are extremely distant, the reports of cosmic rays exceeding $10^{20}$eV -beyond the Greisen-Zatsepin-Kuzmin limit, and strong evidence for neutrino oscillation from atmospheric neutrino data. At the close of millenium, the hadronic sky is being probed with first generation neutrino detectors. They constitute bold, but essential, first steps toward the realization of multi-messenger astronomy. However, much larger facilities of kilometer-scale dimensions are required to examine the sky at sensitivities beginning to approach scientific consensus. Given suitable instrumentation, it is not unreasonable to imagine that the insights revealed by the neutrino messenger of the hadronic sky will soon rival those deduced by observing the electromagnetic sky. This is the challenge for the next millenium.
Figure 9: Example of event which is reconstructed to have an upward going trajectory in AMANDA-B10. Circle sizes are proportional to signal amplitudes.
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