I INTRODUCTION

Of all high-energy particles, only neutrinos can directly convey astronomical information from the edge of the universe—and from deep inside the most cataclysmic high-energy processes. Copiously produced in high-energy collisions, travelling at the velocity of light, and not deflected by magnetic fields, neutrinos meet the basic requirements for astronomy. Their unique advantage arises from a fundamental property: they are affected only by the weakest of nature’s forces (but for gravity) and are therefore essentially unabsorbed as they travel cosmological distances between their origin and us.

Many of the outstanding mysteries of astrophysics may be hidden from our sight at all wavelengths of the electromagnetic spectrum because of absorption by matter and radiation between us and the source. For example, the hot dense regions that form the central engines of stars and galaxies are opaque to photons. In other cases, such as supernova remnants, gamma ray bursters, and active galaxies, all of which may involve compact objects or black holes at their cores, the precise origin of the high-energy photons emerging from their surface regions is uncertain. Therefore, data obtained through a variety of observational windows—and especially through direct observations with neutrinos—may be of cardinal importance.

The sun is an intense source of electron neutrinos ($\nu_e$), albeit of relatively low energy. Solar neutrino astronomy began with first experiments in the mid-1960s; today there are five complementary neutrino detectors viewing the nuclear reactions in the core of the sun and, at the same time, studying the fundamental properties of neutrinos. The sun remained the only astronomical object studied with neutrinos until neutrinos from Supernova 1987A were observed. These are still the only two sources marking the astronomical neutrino spectrum.

Suggestions to use a large volume of water for high-energy neutrino astronomy were made as early as the 1960s [1]. In this case, a muon neutrino ($\nu_\mu$) interacts with a hydrogen or oxygen nucleus in the water and produces a muon travelling in nearly the same direction as the neutrino. The blue Čerenkov light emitted along the muon’s ~kilometer-long trajectory is detected by strings of photomultiplier tubes deployed deep below the surface. DUMAND, a pioneering project located off the

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coast of Hawaii, demonstrated that muons could be detected by this technique [2],
but the planned detector was never realized. A detector composed of about ninety
photomultiplier tubes (or optical modules) located deep in Lake Baikal was the
first to demonstrate the detection of neutrino-induced muons in natural water [3].
The European collaborations ANTARES [4] and NESTOR [5] plan to deploy large-
area detectors in the Mediterranean Sea within the next few years. The NEMO
Collaboration is conducting a site study for a future kilometer-scale detector in the
Mediterranean [6].

The AMANDA collaboration, situated at the U.S. Amundsen-Scott South Pole
Station, has strikingly demonstrated the merits of natural ice as a Čerenkov detector medium [7,8]. In 1996, AMANDA was able to observe atmospheric neutrino
candidates using only 80 eight-inch photomultiplier tubes [7]. With 1997 data,
with 302 optical modules instrumenting approximately 6000 tons of ice, AMANDA
extracted several hundred atmospheric neutrino events. AMANDA was the first
neutrino telescope with an effective area in excess of 10,000 square meters for TeV
muons. In January 2000, AMANDA-II was completed. It consists of 19 string
with a total of 677 OMs arranged in concentric circles, with the ten strings from
AMANDA forming the central core of the new detector. AMANDA has met the
key challenge of neutrino astronomy: it has developed a reliable, expandable, and
affordable technology for deploying a kilometer-scale neutrino detector named Ice-
Cube.

IceCube and the detectors to be located in the Mediterranean Sea will be comple-
mentary in several respects. First and foremost, they will cover different portions of
the sky. (From its location at the South Pole, IceCube observes the northern sky.)
Because of the different properties of Antarctic ice and ocean water—ice scatters
light more but absorbs it less—IceCube should have better energy resolution and
a larger effective area for neutrino detection, while the deep sea detectors should
have somewhat higher pointing resolution. Finally, one of the key challenges in
neutrino astronomy has been the ability to deploy and maintain optical modules
far below the surface; here, too, ice and ocean are essentially different.

II SCIENTIFIC GOALS

The many questions a high-energy neutrino telescope can address naturally begin
with astronomy, both nearby in the universe and far away. Fascinating issues in
particle physics and other branches of science are accessible as well.

Neutrino telescopes will investigate the engines which power active galaxies, the
nature of gamma-ray bursts, and the origin of the highest-energy cosmic rays. They
will search for galactic supernovae, for the births of the supermassive black holes
which power quasars, and for the annihilation products of halo cold dark matter
particles (WIMPS and supersymmetric particles). They can perform coincidence
experiments with Earth- and space-based gamma-ray observatories, cosmic ray
detectors, and even with future gravitational wave detectors such as LIGO.
For guidance in estimating expected signals, we make use of the observed energy in high energy cosmic-ray protons and nuclei as well as in known sources of non-thermal, high-energy gamma radiation. Some fraction of cosmic rays will interact in their sources, whatever they may be, to produce pions. These interactions may be hadronic collisions with ambient gas or photoproduction with intense photon fields near the high-energy sources. In either case, the neutral pions decay to photons while charged pions include neutrinos among their decay products with spectra related to the observed $\gamma$-ray spectra. Estimates based on this relationship show that a kilometer-scale detector is needed to see the neutrino signals [9].

The observed fluxes of cosmic rays and gamma rays set the scale of neutrino telescopes. If we, for instance, assume that gamma ray bursts are the cosmic accelerators of the highest energy cosmic rays, one can calculate from textbook particle physics how many neutrinos are produced when the particle beam coexists with the observed MeV photons in the original fireball. We thus predict the observation of order 10–100 neutrinos of PeV energy per year in a detector with a kilometer-square effective area. The rate is somewhat smaller when assuming instead that the observed cosmic ray beam originates near supermassive black holes at the center of active galaxies. Interaction of the cosmic rays with the abundant UV light in the galaxy is the source of the observed neutrinos. For detailed reviews, see reference [10].

TeV $\gamma$-rays may be produced by radiative processes from accelerated electrons, whereas neutrinos must be produced by hadronic processes. Therefore, high-energy neutrino astronomy has the potential to discriminate between hadronic and electromagnetic models for the intriguing TeV emission from objects such as supernova remnants, gamma-ray burst sources and active galactic nuclei. With this capability, neutrino telescopes may resolve unambiguously one of the oldest puzzles in science: the origin of cosmic rays. TeV photon fluxes determine, independently from the cosmic ray flux, the scale of the neutrino telescope. If one assumes that the observed TeV gamma rays emitted by blazars and supernova remnants are the decay products of neutral pions, one can estimate the accompanying flux of neutrinos in a largely model-independent way. One anticipates neutrino rates of order a few events per year from the Crab and the observed Markarian sources to, possibly, a few hundred from Sgr A [11]. The conclusion is, once more, that a kilometer-scale instrument is required to confirm or rule out the hadronic origin of the highest energy photons.

With high-energy neutrino astrophysics, we are poised to open a new window into space and back in time to the highest-energy processes in the universe. The potential scientific payoff of neutrino astronomy arises from the great penetrating power of neutrinos, which allows them to emerge from dense inner regions of energetic sources. It necessarily follows that the expected interaction rates are small, even with a kilometer-scale detector. History has shown, however, that the opening of each new astronomical window has led to unexpected discoveries. Thus, for example, there could be hidden particle accelerators from which only the neutrinos escape. Yet the science these instruments may do which we cannot anticipate, may
well fuel the quest for astronomical knowledge in the next century. Unexpected discovery has followed the inauguration of most new astronomical instruments. Large reflecting telescopes on mountaintops led to the discovery of distant galaxies and an expanding universe; radio telescopes found the cosmic microwave background; X-ray and gamma-ray satellites have uncovered a bestiary of awesome cosmological objects. Even the first modest solar-neutrino observatory revealed a paradox about the nature of fundamental interactions which is yet to be fully explained. No one can predict all that a high-energy neutrino observatory will find in the sky—except that it is very likely to amaze us.

III LARGE NATURAL ČERENKOV DETECTORS

The first generation of neutrino telescopes, launched by the bold decision of the DUMAND collaboration to construct such an instrument, are designed to reach a large telescope area and detection volume for a neutrino threshold of order 10 GeV. This relatively low threshold permits calibration of the novel instrument on the known flux of atmospheric neutrinos. The architecture is optimized for reconstructing the Čerenkov light front radiated by an up-going, neutrino-induced muon. Only up-going muons made by neutrinos reaching us through the Earth can be successfully detected. The Earth is used as a filter to screen the fatal background of cosmic ray muons. This makes neutrino detection possible over the lower hemisphere of the detector. Up-going muons must be identified in a background of down-going, cosmic ray muons which are more than $10^5$ times more frequent for a depth of 1~2 kilometers. The method is sketched in Fig. 1.

![Figure 1](image-url)

**FIGURE 1.** The arrival times of the Čerenkov photons in 6 optical sensors determine the direction of the muon track.

The optical requirements of the detector medium are severe. A large absorption length is required because it determines the spacings of the optical sensors and, to a significant extent, the cost of the detector. A long scattering length is needed to preserve the geometry of the Čerenkov pattern. Nature has been kind and offered
ice and water as adequate natural Čerenkov media. Their optical properties are, in fact, complementary. Water and ice have similar attenuation length, with the role of scattering and absorption reversed. Optics seems, at present, to drive the evolution of ice and water detectors in predictable directions: towards very large telescope area in ice exploiting the long absorption length, and towards lower threshold and good muon track reconstruction in water exploiting the long scattering length.

A Baikal, ANTARES, Nestor and NEMO: Northern Water

Whereas the science is compelling, the real challenge is to develop a reliable, expandable and affordable detector technology. With the termination of the pioneering DUMAND experiment, the efforts in water are, at present, spearheaded by the Baikal experiment [3]. The Baikal Neutrino Telescope is deployed in Lake Baikal, Siberia, 3.6 km from shore at a depth of 1.1 km. An umbrella-like frame holds 8 strings, each instrumented with 24 pairs of 37-cm diameter QUASAR photomultiplier tubes (PMT). Two PMTs in a pair are switched in coincidence in order to suppress background from natural radioactivity and bioluminescence. Operating with 144 optical modules since April 1997, the NT-200 detector has been completed in April 1998 with 192 optical modules (OM). The Baikal detector is well understood, and the first atmospheric neutrinos have been identified.

The Baikal site is competitive with deep oceans, although the smaller absorption length of Čerenkov light in lake water requires a somewhat denser spacing of the OMs. This does, however, result in a lower threshold which may be a definite advantage, for instance for oscillation measurements and WIMP searches. They have shown that their shallow depth of 1 kilometer does not represent a serious drawback. By far the most significant advantage is the site with a seasonal ice cover which allows reliable and inexpensive deployment and repair of detector elements from a stable platform.

With data taken with 96 OMs only, they have shown that atmospheric muons can be reconstructed with sufficient accuracy to identify atmospheric neutrinos; see Fig. 2. The neutrino events are isolated from the cosmic ray muon background by imposing a restriction on the chi-square of the Čerenkov fit, and by requiring consistency between the reconstructed trajectory and the spatial locations of the OMs reporting signals. In order to guarantee a minimum lever arm for track fitting, they only consider events with a projection of the most distant channels on the track larger than 35 meters. This does, of course, result in a higher threshold.

In the following years, NT-200 will be operated as a neutrino telescope with an effective area between $10^3 \sim 5 \times 10^3$ m$^2$, depending on energy. Presumably too small to detect neutrinos from extraterrestrial sources, NT-200 will serve as the prototype for a larger telescope. For instance, with 2000 OMs, a threshold of $10 \sim 20$ GeV and an effective area of $5 \times 10^4 \sim 10^5$ m$^2$, an expanded Baikal telescope would fill the gap between present underground detectors and planned
FIGURE 2. Angular distribution of muon tracks in the Lake Baikal experiment after the cuts described in the text.

high threshold detectors of cubic kilometer size. Its key advantage would be low threshold.

The Baikal experiment represents a proof of concept for deep ocean projects. These have the advantage of larger depth and optically superior water. Their challenge is to find reliable and affordable solutions to a variety of technological challenges for deploying a deep underwater detector. Several groups are confronting the problem; both NESTOR and ANTARES are developing rather different detector concepts in the Mediterranean.

The NESTOR collaboration [5], as part of a series of ongoing technology tests, is testing the umbrella structure which will hold the OMs. They have already deployed two aluminum “floors”, 34 m in diameter, to a depth of 2600 m. Mechanical robustness was demonstrated by towing the structure, submerged below 2000 m, from shore to the site and back. These tests should soon be repeated with fully instrumented floors. The actual detector will consist of a tower of 12 six-legged floors vertically separated by 30 m. Each floor contains 14 OMs with four times the photocathode area of the commercial 8 inch photomultipliers used by AMANDA and ANTARES.

The detector concept is patterned along the Baikal design. The symmetric up/down orientation of the OMs will result in uniform angular acceptance and the relatively close spacings in a low threshold. NESTOR does have the advantage of a superb site off the coast of Southern Greece, possibly the best in the Mediterranean. The detector can be deployed below 3.5 km relatively close to shore. With
the attenuation length peaking at 55 m near 470 nm the site is optically superior to that of all other deep water sites investigated for neutrino astronomy.

The ANTARES collaboration [4] is investigating the suitability of a 2400 m-deep Mediterranean site off Toulon, France. The site is a trade-off between acceptable optical properties of the water and easy access to ocean technology. Their detector concept indeed requires remotely operated vehicles for making underwater connections. First results on water quality are very encouraging with an attenuation length of 40 m at 467 nm and a scattering length exceeding 100 m. Random noise exceeding 50 kHz per OM is eliminated by requiring coincidences between neighboring OMs, as is done in the Lake Baikal design. Unlike other water experiments, they will point all photomultipliers sideways in order to avoid the effects of biofouling. The problem is significant at the Toulon site, but only affects the upper pole region of the OM. Relatively weak intensity and long duration bioluminescence results in an acceptable deadtime of the detector. They have demonstrated their capability to deploy and retrieve a string, and have reconstructed down-going muons with 8 OMs deployed on the test string.

With the study of atmospheric neutrino oscillations as a top priority, they had planned to deploy in 2001-2003 10 strings instrumented over 400 m with 100 OMs. After study of the underwater currents they decided that they can space the strings by 100 m, and possibly by 60 m. The ANTARES detector will consist of 13 strings, each equipped with 30 storeys and 3 PMTs per storey. The large photocathode density of the array will allow the study of atmospheric neutrino oscillations in the range $255 < L/E < 2550$ km GeV$^{-1}$ with neutrinos in the energy range $5 < E_\nu < 50$ GeV. This detector will have an area of about $3 \times 10^4$ m$^2$ for 1 TeV muons — similar to AMANDA-II — and is planned to be fully deployed by the end of 2003.

A new R&D initiative based in Catania, Sicily has been mapping Mediterranean sites, studying mechanical structures and low power electronics. One must hope that with a successful pioneering neutrino detector of $10^{-3}$ km$^3$ in Lake Baikal, a forthcoming $10^{-2}$ km$^3$ detector near Toulon, the Mediterranean efforts will converge on a $10^{-1}$ km$^3$ detector possibly at the NESTOR site [12]. For neutrino astronomy to become a viable science several of these, or other, projects will have to succeed besides AMANDA. Astronomy, whether in the optical or in any other wave-band, thrives on a diversity of complementary instruments, not on “a single best instrument”. When, for instance, the Soviet government tried out the latter method by creating a national large mirror project, it virtually annihilated the field.

**B AMANDA: Southern Ice**

Construction of the first-generation AMANDA detector was completed in the austral summer 96–97. It consists of 302 optical modules deployed at a depth of 1500–2000 m; see Fig. 3. Here the optical module consists of an 8-inch photomultiplier tube and nothing else. It is connected to the surface by a cable which transmits the HV as well as the anode current of a triggered photomultiplier. The
instrumented volume and the effective telescope area of this instrument matches those of the ultimate DUMAND Octagon detector which, unfortunately, could not be completed.

FIGURE 3. The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 metres in the inner strings 1-4, and by 10 metres in the outer strings 5-10. The colored circles show pulses from the photomultipliers for a particular event; the size of the circles indicate the size of the pulse and the colors the time of the photons arrival. Earlier times are in red and later ones in blue. The arrow indicates the reconstructed track of the up-going muon.

Depending on depth, the absorption length of blue and UV light in the ice varies between 85 and 225 metres. The effective scattering length, which combines the mean-free path $\lambda$ with the average scattering angle $\theta$ as $\lambda \left(1 - \langle \cos \theta \rangle \right)$, varies from 15 to 40 metres [13]. Because the absorption length of light in the ice is very long and the scattering length relatively short, many photons are delayed by scattering. In order to reconstruct the muon track one uses maximum likelihood methods, which take into account the scattering and absorption of photons as determined from calibration measurements [7]. A Bayesian formulation of the likelihood, which takes into account the much larger rate of down-going tracks relative to up-going signal, has been particularly effective in decreasing the chance for a down-going muon to be misreconstructed as upward-going.

Other types of events that might appear to be up-going muons must also be considered and eliminated. Rare cases, such as muons which undergo catastrophic energy loss, for instance through bremsstrahlung, or that are coincident with other
muons, must be investigated. To this end, a series of requirements or quality criteria, based on the characteristic time and spatial pattern of photons associated with a muon track and the response of the detector, are applied to all events that, in the first analysis, appear to be up-going muons. For example, an event which has a large number of optical modules hit by photons unscattered relative to the expected Cherenkov times of the reconstructed track, has a high quality. By making these requirements (or “cuts”) increasingly selective we eliminate correspondingly more of the background of false up-going events while still retaining a significant fraction of the true up-going muons, i.e., the neutrino signal. Two different and independent analyses of the same set of data covering 138 days of observation have been undertaken. These analyses yielded comparable numbers of upgoing muons (153 in analysis A, 188 in analysis B). Comparison of these results with their respective Monte Carlo simulations shows that they are consistent with each other in terms of the numbers of events, the number of events in common, and the expected properties of atmospheric neutrinos.

In Fig. 4, from analysis A, the experimental events are compared to simulations of background and signal as a function of the (identical) quality requirements placed on the three types of events: experimental data, simulated up-going muons from atmospheric neutrinos, and a simulated background of down-going cosmic-ray muons. For simplicity in presentation, the levels of the individual types of cuts have been combined into a single parameter representing the overall event quality, and the comparison is made in the form of ratios. Figure 4 shows events for which the quality level is 4 and higher. As the quality level is increased further, the ratios of simulated background to experimental data and experimental data to simulated signal both continue their rapid decrease, the former toward zero and the latter toward unity. Over the same range, the ratio of experimental data to the simulated sum of background and signal remains near unity. At an event quality of 6.9 there are 153 events in the sample of experimental data and the ratio to predicted signal is 0.7. The conclusion is that the quality requirements have reduced the events from misreconstructed down-going muons in the experimental data to a negligible fraction of the signal and that the experimental data behave in the same way as the simulated atmospheric neutrino signal for events that pass the stringent cuts. The remaining instrumental background is estimated at $15\pm7\%$ of the signal.

The estimated uncertainty on the number of events predicted by the signal Monte Carlo simulation, which includes uncertainties in the high-energy atmospheric neutrino flux, the in-situ sensitivity of the optical modules, and the precise optical properties of the ice, is $+40\% \text{ -- } -50\%$. The observed ratio of experiment to simulation (0.7) and the expectation (1.0) therefore agree within errors.

The shape of zenith angle distribution from analysis B is compared to a simulation of the atmospheric neutrino signal in Fig. 5 in which the two distributions have been normalized to each other. The variation of the measured rate with zenith angle is reproduced by the simulation to within the statistical uncertainty. Note that the tall geometry of the detector strongly influences the dependence on zenith angle in favor of more vertical muons.
FIGURE 4. Reconstructed muon events are compared to simulations of background cosmic ray muons (BG MC) and simulations of atmospheric neutrinos (Signal MC atm $\nu$) as a function of “event quality”, a variable indicating the severity of the cuts designed to enhance the signal. Note that the comparison is made in the form of ratios.

FIGURE 5. Reconstructed zenith angle distribution. The points mark the data and the shaded boxes a simulation of atmospheric neutrino events, the widths of the boxes indicating the error bars. The overall normalization of the simulation has been adjusted to fit the data.
Estimates of the energies of the up-going muons (based on simulations of the number of optical modules that participate in an event) indicate that the energies of these muons are in the range from 100 GeV to $\sim 1$ TeV. This is consistent with their atmospheric neutrino origin.

The agreement between simulation and experiment shown in Figures 4 and 5 taken together with other comparisons of measured and simulated events [14] leads to the conclusion that the up-going muon events observed by AMANDA are produced mainly by atmospheric neutrinos.

The arrival directions of the neutrinos observed in both analyses are shown in Fig. 6. A statistical analysis indicates no evidence for point sources in this sample. An estimate of the energies of the up-going muons (based on simulations of the number of reporting optical modules) indicates that all events have energies consistent with an atmospheric neutrino origin. This enables us to reach a level of sensitivity to a diffuse flux of high energy extra-terrestrial neutrinos of order $dN/dE_\nu = 10^{-6}E_\nu^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$, assuming an $E^{-2}$ spectrum. At this level we would exclude a variety of theoretical models which assume the hadronic origin of TeV photons from active galaxies and blazars. Searches for neutrinos from gamma-ray bursts, for magnetic monopoles, and for a cold dark matter signal from the center of the Earth are also in progress and, with only 138 days of data, yield limits comparable to or better than those from smaller underground neutrino detectors that have operated for a much longer period.

![FIGURE 6. Distribution in declination and right ascension of the upgoing events on the sky.](image-url)

Data are being taken now with the larger array, AMANDA-II. New surface electronics consolidates several triggering functions and adds functionality. New scalers were installed that provide millisecond resolution — important for Supernova studies. Several technologies were deployed to evaluate their utility and readiness for future expansion to larger systems.

Yet, the fluxes of very high energy neutrinos predicted by theoretical models or derived from the observed flux of ultra high energy cosmic rays are sufficiently low that a neutrino detector having an effective area up to a square kilometer is
required for their observation and study [9]. Plans are therefore being made for a much larger detector, IceCube, consisting of 4800 photomultipliers to be deployed on 80 strings. This proposed neutrino telescope would have an effective area of \( \sim 1 \, \text{km}^2 \), an energy threshold near 100 GeV and pointing accuracy for muons better than one degree for high energy events. In conclusion, the observation of atmospheric neutrinos reported here for AMANDA is a significant step toward establishing the field of neutrino astronomy first envisioned over 40 years ago.

Although neutrino telescopes are intended primarily for TeV (and higher) energy neutrino astronomy, AMANDA and IceCube also have the potential to detect the burst of several-MeV neutrinos from a galactic supernova and possibly even an extragalactic burst of low-energy neutrinos associated with the birth of a massive black hole. By continuously monitoring the summed counting rate of its 4800 optical modules, ice detectors will monitor the sky for such cataclysmic phenomena. The interactions of this host of low-energy neutrinos will be distributed uniformly throughout the detector, a signal rising above the background noise level. The very low noise rate for an optical module in ice (as opposed to the very high noise rates in ocean water) makes it possible to continue this “supernova watch,” already begun by AMANDA [15].

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