

DUMAND AND AMANDA: HIGH ENERGY NEUTRINO ASTROPHYSICS

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ABSTRACT

The field of high energy neutrino astrophysics is entering an exciting new phase as two, new, large-scale observatories prepare to come on line. Both DUMAND (Deep Underwater Muon and Neutrino Detector) and AMANDA (Antarctic Muon and Neutrino Detector) had major deployment efforts in December 1993–January 1994. Results were mixed, with both projects making substantial progress, but encountering setbacks that delayed full-scale operation. The achievements, status, and plans (as of October 1994) of these two projects will be discussed.

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1 Introduction

Nature must love neutrinos, because she makes so many of them. Neutrinos are more abundant than photons (about $10^3/\text{cm}^3$; $10^{17}/\text{sec}$ pass through your body). In addition to the enormous density of Big Bang relict neutrinos, effectively undetectable due to their tiny energy, neutrinos are produced copiously at solar (few MeV) and astrophysical (GeV–EeV) energy scales by a variety of processes.

Since neutrinos are uncharged, (probably) massless leptons, they interact with matter only via the weak force. Thus, while they share some features with photons as a probe of the distant universe (straight-line propagation from sources at the speed of light), they offer the advantage of being able to penetrate regions with moderate mass density such as the center of our galaxy. Neutrinos therefore let us observe regions of the universe as yet unseen. High energy photons and neutrinos are produced by similar processes, for example, by the decay of mesons produced in hadronic interactions of charged particles near a cosmic ray source. Compact binary systems, in which a neutron star orbits a giant companion, are excellent candidates for copious photon and neutrino production, as protons are accelerated in the pulsar’s intense, rapidly changing magnetic fields, and interact in the periphery of the companion star. One therefore expects to see neutrinos from sources that produce high energy gamma rays. While current experiments have seen clear gamma ray signals from only a few identifiable point sources,¹ this almost certainly must be due to experimental limitations. We know that cosmic ray hadrons (protons and/or nuclei) are produced in the EeV (10^{18} eV) region beyond the reasonable limit for supernova shock acceleration (thought to account for most of the cosmic ray flux below 10^{15} eV), and if protons are accelerated, there must be interactions near the sources yielding photons and neutrinos.

Other source mechanisms are unique to neutrinos, such as the widely accepted models for abundant UHE neutrino production in Active Galactic Nuclei (AGNs).² Here, the power source is thought to be a black hole about 10^{6-9} times as massive as the Sun, protons are accelerated by shocks in jets or flow in the accretion disk, and neutrinos are produced by interactions with the high density of UV or optical photons near the nucleus. Model calculations show that we should expect a neutrino spectrum much harder than the normal cosmic ray spectrum, leading to a previously-unexpected wealth of neutrinos in the PeV (10^{15} eV) range (Fig. 1), making practical secondary studies such as tomography of the Earth’s core. Neu-

trino observations in the GeV–PeV range thus complement photon observations at all energies and provide useful discrimination between some models.^{3,4}

There are basic physics questions to be answered. Why do neutrinos come in three flavors, do they have mass, and are they the solution to the dark-matter puzzle? As an example, recent results from the Kamiokande-III⁵ and IMB⁶ underground neutrino detectors suggest a substantial deviation from expectation in the observed ratio of muon to electron neutrinos produced in the atmosphere; it is possible to interpret the data in terms of neutrino oscillations, consistent with an island of allowed values in the mixing-angle/mass-difference parameter space. Neutrino astrophysics experiments like these provide a way to address such questions with costs an order of magnitude below those of contemporary accelerator experiments, i.e., on the order of US \$10 million). There is no question that in the future, we will have to find ways to do particle physics that make much smaller demands on the world economy.

But for many of us, one of the most attractive features of neutrino astrophysics is the virginity of the field. The unexpected is always a possibility, and historically, science has made great advances whenever a new mode of viewing the universe has been tested. Perhaps the first large-scale neutrino detectors will eventually have the significance of Galileo’s spyglass.

The basic concept of a water or ice Cherenkov detector is illustrated in Fig. 2, which depicts a neutrino interaction producing a muon. Seawater (or ice) serves a triple purpose, acting as a low-cost massive target, supplying a track sensitive, transparent medium for production and propagation of Cherenkov radiation by charged particles, and also providing a thick, uniform overburden (in contrast to underground experiments, with nonuniform material and an irregular surface profile) to filter out downward-moving background particles. The water volume is instrumented with an array of sensitive photomultiplier tubes (PMTs). The attenuation length for light in water at the DUMAND site in the appropriate wavelength range is about 40 m, which defines the scale of the transverse spacing of detector “strings,” and the vertical separation of PMTs is set at 10 m to provide adequate photocathode coverage; similar parameters apply to ice. Upward moving neutrinos, having passed through the earth (and thus being accompanied by essentially no background, as shown in Fig. 3), interact in the contained volume of water or in the nearby seabed, producing muons, charged particles moving near the speed of light *in vacuo*, which will therefore generate Cherenkov radiation in the

Figure 1: Expected rates (events per year) in DUMAND-II from AGN neutrinos from several leading models.

water ($n=1.35$ in seawater). The Cherenkov light is produced in a characteristic cone-shaped pattern, and thus information on the arrival time and pulse intensity recorded at each of the photomultiplier tubes can be used to reconstruct the muon track direction. For energetic muons, collected photoelectron statistics can be sufficient to provide a muon-energy estimate. In the case of “contained events,” where the event vertex is within the sensitive volume, the hadron-electromagnetic cascade can be observed and a more accurate energy estimate made.

The idea of detecting high energy astrophysical neutrinos is an old one, and calls for development of a practical detector date from at least the early '60s.⁷ Apparent anomalies in the underground muon flux⁸ stimulated interest in underwater muon detectors offering uniform overburden and indirectly fostered development of the current generation of large-scale neutrino detectors.⁹ The DUMAND concept in more or less its present form has been discussed, and construction projects of various degrees of practicality have been proposed since the mid-'70s.¹⁰ The water Cherenkov technique was further refined in the early '80s by the successful construction and operation of large-scale proton-decay detectors (later used as low-energy neutrino observatories) by the IMB¹¹ and Kamiokande¹² Collaborations. These projects made it possible for the DUMAND proposal to be accepted for construction funding by the U.S. Department of Energy in 1990. The cost and risks involved in deep-ocean engineering operations were still a matter of concern. At about the same time, the AMANDA group proposed an alternative approach in which the Antarctic ice cap replaces the ocean as overburden, target, and detecting medium. Deployment operations take place from the stable platform of the South Pole Station. AMANDA has its substantial logistical requirements covered by the U.S. National Science Foundation's Office of Polar Programs, which supports all scientific research operations in Antarctica.

The remainder of this article will compare and contrast AMANDA and DUMAND, ending with a look at initiatives presently being undertaken for the next step in detector sensitivity, a second-generation observatory of scale 1 km^3 . As a participant in DUMAND, I hope to avoid any inadvertent bias in this review. Two parallel efforts in Europe, the NESTOR project in Greece and the Baikal project in Russia, will not be discussed here simply due to lack of space. Both projects are making significant progress and will have important effects on the development of this rapidly-growing field.

Figure 2: Water (or ice) Cherenkov detector concept.

Figure 3: Muon angular distribution: background muons from atmospheric cosmic ray interactions are cut off by looking only at upward-moving tracks.

2 DUMAND

Taking our subjects in order of age, the DUMAND project has been discussed in one form or another for nearly 30 years.¹³ The detector presently being constructed in Hawaii is called DUMAND-II.¹⁴ DUMAND-I refers to a ship-suspended single prototype string which was successfully operated in 1987.¹⁵ The funding plan provides for deployment of the full nine-string array (Fig. 4) in two phases: first three strings (the triad) as a demonstration, and the remaining six strings (complete octagon, plus center string) after about one year of testing and operation. Details of the detector design and physics capabilities have been published elsewhere.¹⁶

The Island of Hawaii was selected for a variety of compelling reasons: exceptional water clarity, proximity of an abyssal plain with appropriate seabed characteristics to a suitable shore site (30 km away), presence of an active particle physics group at the nearby University of Hawaii in Honolulu, and preexisting laboratory infrastructure at the shore site, due to an ocean thermal energy research project. The latter feature even provided a cost-free conduit for the DUMAND shore cable to pass beneath the surf zone, since the thermal energy project involves slant drilling of tunnels into the ocean.

When completed, DUMAND-II will be an array of 216 Optical Modules (OMs are photomultiplier tubes plus front-end electronics encased in a standard glass oceanographic pressure sphere) deployed on nine vertical strings, which are moored in an octagonal pattern with 40 m sides and one string in the center (Fig. 4). The instrumented portion of each string begins 100 m above the ocean floor to avoid boundary-layer effects. In addition to OMs, the strings include sets of hydrophones and other acoustical equipment, as well as calibration modules, in which a constant output laser light source is used to excite a scintillator ball viewed by the PMTs.

The array is being deployed on the ocean floor at depth 4800 m, 30 km due west from the Kona Coast of the Island of Hawaii (Fig. 5), and is connected to the shore laboratory at Keahole Point by a cable combining electrical and fiber optic elements, terminating in an underwater junction box. The shore cable contains 12 fibers (including spares) and a copper layer which supplies 5 kW of electrical power at 350 VDC, using a seawater return system. Figure 6 shows an overall block diagram for the DUMAND detector system. The underwater site places no

Figure 4: DUMAND-II underwater neutrino detector array.

inherent limitation on possibilities for future expansion of the detector. With all nine strings in place, DUMAND will have an effective detection area of 20,000 m², instrumenting a column of water which has the height of the Eiffel Tower and its width at the base.

Signals from the PMTs are preprocessed within the optical modules (Fig. 7), providing standard pulses which encode time of arrival (to ~ 1 ns accuracy), pulse area, and time-over-threshold (TOT), a measure of pulse duration. Data from the 24 OMs on each string are digitized and serialized in the string controller module by a custom 27-channel (including spares and housekeeping) monolithic GaAs TDC/buffer/multiplexer chip which operates with 1.25 nsec timing precision and two-level internal buffers. The data stream is sent to shore via optical fibers (one per string) at 0.5 GHz. A separate optical fiber carries environmental and acoustical ranging information which is used to measure the geometry of the array.

The data system has been designed to cope with the background rate from radioactivity in the water (primarily from natural ^{40}K) and bioluminescence and still generate minimal deadtime for recording neutrino events. Results from the 1993 deployment confirmed observations made in the 1987 DUMAND-I experiment.¹⁷ As Fig. 8 shows, the dark counting rate for a single OM was found to be on the order of 60 kHz, primarily due to trace ^{40}K in the huge volume of seawater each tube views. Noise due to bioluminescence is episodic and likely to be unimportant after the array has been stationary on the ocean bottom for some time, since the light-emitting microscopic creatures are stimulated by motion. ^{40}K and bioluminescence contribute mainly one photoelectron hits distributed randomly in time over the entire array.

The raw information is sent to the shore station 30 km away for processing. The trigger system looks for patterns in time, space, and pulse height in the OM signals consistent with the passage of charged particles through the array. Events satisfying the trigger criteria are recorded for further off-line analysis.

Since 1992, DUMAND teams have been preparing the site and testing underwater assembly operations. DUMAND-II requires a reasonably flat site with appropriate soil-bearing properties. The selected site has been marked with acoustical transponders which have been accurately surveyed in geophysical (GPS) coordinates (Fig. 9), and its suitability was verified remotely by acoustical imaging, film camera, and video recordings; in addition, DUMAND personnel have cruised the area in a manned submarine, the U.S. Navy's *DSV Sea Cliff*, to verify that

Figure 5: DUMAND site off the Big Island of Hawaii.

Figure 6: Block diagram of the DUMAND detector system.

Figure 7: DUMAND optical module.

the site is flat and free of any undesirable features. These preliminary operations also confirmed the exceptional clarity of the water, with an attenuation length of about 40 m in the appropriate wavelength band.

We need to point reconstructed muon tracks onto the celestial sphere with an accuracy better than 1° (the median angle between primary ν and secondary μ at 1 TeV). This means that relative OM locations must be known to the order of a few centimeters, and the overall geographical orientation of the array must be known to much better than 1° . The Global Positioning Satellite (GPS) system plus conventional oceanographic acoustical survey techniques allow us to measure the geographical coordinates of underwater fiducials (acoustical transponders) to within a few meters, satisfying the geographical orientation requirement. We were unable to find a commercial system able to reliably provide the OM positioning accuracies required, so we designed our own sonar system, which measures acoustical signal transit times with 10 μ sec precision using frequency-modulated chirps and matched filtering via DSPs.¹⁸ Other components of the environmental monitoring system measure oceanographic parameters such as water currents, temperature, and salinity (needed to calculate the local speed of sound).

In December of 1993, the DUMAND scientific team and the crew of the University of Washington oceanographic ship *R/V Thomas G. Thompson* successfully deployed the first major components of DUMAND, including the junction box, the environmental module, and the shore cable, with one complete OM string attached to the junction box. Other DUMAND personnel prepared the shore station for operation. The procedures for the lowering and cable laying operations had been worked out in practice runs. Cable laying equipment was leased and mounted on the ship. Environmental monitoring equipment and the site-defining navigational sonar array were also laid out and used in the deployment operation.

The basic infrastructure for DUMAND, comprising the underwater junction box, the 30 km optical fiber/copper cable to shore, and the shore station facility, are now in place. The deployed string was used to record backgrounds and muon events. Unfortunately, an undetected flaw in one of over 100 electrical penetrators (connectors) used for the electronics pressure vessels produced a small water leak. Seawater eventually shorted out the string controller electronics, disabling further observations after about ten hours of operation. In January 1994, the disabled

Figure 8: Singles rates in a typical DUMAND optical module. The histogram shows the mean counting rate over a series of 0.2 sec recording intervals. The quiescent rate is about 60 kHz, with occasional intervals showing spikes above 100 kHz due to bioluminescence.

Figure 9: Contour map of the DUMAND site (depths in meters below sea level), showing placement of acoustical transponders, junction box, and cable as surveyed during the December 1993 deployment operation.

string was remotely released by an acoustical signal, recovered at sea, and returned to Honolulu for diagnosis and repair. The fault has been analyzed and quality assurance procedures to avoid future recurrences have been put in place.

In addition to the refurbished first string, two further strings are currently undergoing final assembly and testing. We plan to make extensive deep water tests of these three strings before mooring them at the DUMAND site. Surface ship and underwater vehicle resources needed to carry out deployment and interconnection operations will be available in 1995.

After redeployment of the first string of OMs, each successive string will be moored at the vertices of an octagon at a radius of 40 m. Acceptable placement error is about 5 m; this tolerance can be readily achieved using available ships with dynamic positioning capability (basically, GPS navigation coupled to the ship's thrusters), according to simulation studies performed by a marine operations consulting firm. Strings will be connected to the junction box by an umbilical cable and wet-mateable electrical/fiber-optic connector. Using a mockup junction box and string mooring, the U.S. Navy's Advanced Tethered Vehicle (ATV) carried out successful tests of the connecting operation in 1992, proving that tethered remotely operated vehicles (ROVs, which are cheaper and more readily available than manned submersibles) are also an option for DUMAND underwater maintenance activities.

Although the success of the DUMAND deployment was marred by the failure of a single penetrator, enough was learned from the limited period of live operation to be confident that it will be possible to complete and operate the whole DUMAND array. The failure provided an undesired but nonetheless useful opportunity to test procedures for recovering faulty equipment from the sea, an essential task for long-term operation. The overall plan is to install and operate three strings as a full-up demonstration, and then proceed to deployment of the remaining six strings after about a year of test operation.

Further information on DUMAND is available via the DUMAND Home Page on the World Wide Web. The URL address is

<http://web.phys.washington.edu/dumand.html>

3 AMANDA

The Antarctic Muon and Neutrino Detector (AMANDA) uses the same fundamental detector concept as DUMAND, but substitutes polar ice for abyssal seawater.²⁰ Photomultiplier tubes are placed in vertical shafts melted into the icecap at the South Pole, and data acquisition is handled in a counting house established at the surface.²¹ The detector layout is depicted in Fig. 10.

This approach exploits two significant advantages of ice as a medium. It is a stable solid, and it is biologically and radiologically sterile. The ice forms a rigid, adaptive support for the OM strings, and thus, the need for measuring OM positions is reduced from a continuous monitoring process to a one-time survey procedure during deployment. Backgrounds due to bioluminescence and natural radioactivity such as ^{40}K are effectively absent, reducing the background noise rate substantially, and allowing lower true event rates per sky pixel to be detected as a significant excess.²²

Only the Antarctic plateau provides a layer of ice of sufficient depth, about 3 km total (although deployment depths are for practical purposes limited to about 2 km). While real logistical costs are very high, the U.S. National Science Foundation operates a vigorous, well-supported research program in Antarctica. One significant result is ample support for the operational aspects of AMANDA from a source independent of conventional particle physics funding. The U.S. South Pole Station is well-equipped and staffed year-round. Access is by air only, and field operations can take place only during the Austral summer season, roughly October through February. A small staff of technicians and scientist volunteers are to remain icebound through the six-month winter season, maintaining experiments and forwarding limited amounts of data to the continental U.S. via satellite links and land lines. While data rates for communications will be improving over the next few years (plans exist to provide the South Pole Station with 56 kB/sec Internet access), AMANDA presently must depend to some extent on suitcases full of tape cassettes for data transfer.

Since the data acquisition system is only a short distance away from the OMs, at the surface of the ice, AMANDA does not require front-end electronics to be built into the optical modules or a local string controller; the OMs, as shown in Fig. 11, are thus just PMTs in a glass pressure sphere (the same type used in DUMAND), connected to the outside world by coaxial cable (which also carries in

Figure 10: AMANDA array. The upper portion was deployed in January 1994, the lower portion is to be deployed in December 1995.

the high voltage power supply). Signal degradation produces some limitations on cable length, but for the relatively shallow depths used thus far and planned for the next stage of deployment, there should be no significant loss of timing information. The advantage of having foolproof, simple, dumb OMs is very tangible.

The remote location, with highly limited access and long supply lines, causes fewer difficulties than might be imagined, although careful planning is essential (and enforced by Antarctic Program management, who have long experience in these matters). One is about 5000 km from the nearest electronics parts store, and half the useful season can be lost waiting for a forgotten item, so the supply of spares and equipment must be thought through very carefully and stringent predeployment testing is required.

An additional problem is the need for fuel to melt holes over one km deep and about 60 cm in diameter for string deployment. The initial deployments took advantage of a cache of surplus aircraft fuel at the South Pole, stored too long to be certifiable for aircraft use but perfectly suitable for ice-melting. This supply has been consumed, and future deployments will require every liter of fuel to be flown in (along with all other supplies). Since the existing shafts (approximately 1 km deep) consumed about 12,000 liters of fuel each, and deeper shafts require disproportionately larger amounts of fuel, this is a serious concern. However, experience from the initial operations led to a more efficient drill design, now under construction, and it is expected that the deeper holes now required can be made without substantially increasing the fuel requirements.

A test string of four 20 cm diameter OMs was successfully deployed and operated at an 800 m depth in 1992. The PMTs used were available from a previous experiment, and OM size was limited by drilling capabilities. Data on the flux of Cherenkov light from down-going muons were interpreted to mean that the ice at ~ 1 km was essentially bubble-free, and results from this test were considered sufficiently promising to proceed to a first-stage deployment of four full strings, each containing 20 OMs, in 1994. In this operation, the drilling system performed very well, operating nearly continuously for about 45 days and drilling holes at the rate of 90 hr/km.

The OM signal characteristics from the 1994 deployment were about as expected: timing resolution about 5 nsec, stable operation with gain 10^8 , and dark noise rate about 2 kHz. Of the 80 OMs deployed, 73 were operating well five months later, a reasonable survival rate. In addition to coaxial cables carrying

Figure 11: AMANDA optical module.

power down and signals up, the strings included optical fibers to distribute calibration signals from a laser source on the surface to each OM. Each optical fiber terminates in a nylon diffusing sphere located 30 cm from its OM.

Unfortunately, laser calibration signals were found to have transit times between diffuser balls and OMs that were much longer than expected for unobstructed straight-line paths. Figure 12 shows two examples of transit time distributions, with the geometrical distance between source and OM corresponding to arrival-time delays of 91 and 142 nsec, respectively.²² As can be seen from the figure, the mean arrival time is more than five times longer, and even the earliest arrivals take nearly twice as long as expected to reach the OMs. These data have been carefully analyzed by the AMANDA group, and the conclusion is that (a) the absorption length of 475 nm photons in polar ice is about 60 meters, but (b) the ice contains a significant density of bubbles which produces an effective scattering length of only 20 cm. Figure 13 shows that the arrival time data provide a good fit to these hypotheses.

The depth dependence of the scattering length is consistent with results from microscopic examination of ice cores from Greenland and Vostok (a Russian Antarctic base). At Vostok, where the altitude and snow accumulation rate differ from the South Pole but the ice temperature profile is similar, core samples show fewer than 0.5 bubbles/cm³ below a 1280 m depth. This gives hope that putting the AMANDA strings only a few hundred meters deeper will eliminate the scattering problem. The strategy therefore will be to deploy the next set of strings in 1995-96, taking advantage of the verified 60 m absorption length to increase OM spacing, and putting the strings in below 1500 m to avoid bubbles. With an increase to 15 m vertical OM spacing, a considerably larger volume can be instrumented. Six strings of 13 OMs each will be deployed in a circular pattern with 60 m radius. The new drilling system may also make it possible to go to larger diameter phototubes, although current plans call for using the same PMTs used in previous deployments.²³

As with DUMAND, the results of the 1994 AMANDA deployment did not include detection of astrophysical neutrinos but did demonstrate important aspects of the technique. Despite the short scattering length, which in effect reduces track reconstruction accuracy to $\pm 10^0$ on the sky, it was possible to perform a number of tests which verified the general viability of the AMANDA concept using the 1994 array. AMANDA has much less overburden than DUMAND, and therefore,

Figure 12: Optical pulse transit time distributions from AMANDA calibration data, for distances of (a) 21 and (b) 32 meters. The expected arrival times for direct paths would be approximately 92 and 140 nsec, respectively. Solid lines show fits to a diffusion model with appropriate effective scattering length (see Fig. 13).

Figure 13: Inverse effective scattering length for light at the AMANDA site as a function of depth in ice.

a much higher background rate due to downward-going muons. However, the absence of bioluminescence and natural radioactivity makes the OM singles noise rate much lower, about 2 kHz as compared to 60 kHz. The mean OM dark noise rates observed (1.8 kHz) are about half what had been anticipated.

Finally, it was possible to operate the strings in coincidence with the South Pole Air Shower Experiment (SPASE), which is located about 800 m away from the AMANDA site. Extensive air showers arriving with zenith angles between 37 and 46 degrees with appropriate azimuth should be seen by both experiments, and this mode of operation has been successfully demonstrated by using SPASE triggers to log AMANDA data.²⁴

Further information on AMANDA is available via the AMANDA Home Page on the World Wide Web. The URL address is

<http://spice2.physics.wisc.edu/amanda2.html>

4 Comparison of AMANDA and DUMAND

The following table compares salient features of the two detectors. In addition to common features, both projects have a set of unique advantages and disadvantages, often in the form of a tradeoff. For example, AMANDA has rigidly fixed OM positions and the ability to locate front-end electronics very near the detector elements on the surface just above the array. On the other hand, DUMAND strings can be readily released and recovered for repair or repositioning, and the use of fiber optic data transmission makes cable length irrelevant. DUMAND's thick seawater overburden greatly reduces event backgrounds due to down-going muons, at the expense of heavier singles rates due to radioactivity and bioluminescence, while AMANDA's ice overburden is less than half as thick but makes no contribution to dark noise. The real costs of deployment are probably about equal, but AMANDA's logistical costs are part of a very large Antarctic research enterprise in which AMANDA is (at present) a small perturbation, while DUMAND's costs are a very visible portion of their budget (although, in fact, ship and submarine time should eventually be available by interagency cooperation). The two groups have had similar outcomes from their first major deployment attempts this year: partial proof of concept, but not the definitive proof offered by unambiguous neutrino detection.

Table 1: **COMPARISON BETWEEN DUMAND AND AMANDA**

| DUMAND | AMANDA |
|--|---|
| <p>Seawater – high noise</p> <ul style="list-style-type: none"> • ^{40}K background • Bioluminescence | <p>Ice – low noise</p> <ul style="list-style-type: none"> • No ^{40}K background • No bioluminescence |
| <p>Deep: 5000 m</p> <ul style="list-style-type: none"> • Low event background • Smart OMs • Digital fiber-optic data transfer • Complex underwater electronics | <p>Shallow: 1000 m</p> <ul style="list-style-type: none"> • High event background • Simple OMs • Analog signals to surface—coax cable • Simple OMs—processing on surface |
| <p>Underwater</p> <ul style="list-style-type: none"> • Track visibility proven • Well-developed commercial technologies • DSV/ROV required • Recoverable after deployment | <p>Under ice</p> <ul style="list-style-type: none"> • Bubbles remain at 1000 m • Environment less well-known • Direct access from surface • Not recoverable once deployed |
| <p>Hawaii</p> <ul style="list-style-type: none"> • Easy access year-round • Local high-tech facilities • Local university group (resident staff planned) • Near-equatorial site: daily scan of celestial midlatitudes | <p>Antarctica</p> <ul style="list-style-type: none"> • Restricted access to site • Limited facilities at site • No permanent residents (but continuous staffing) • Polar site: fixed view of celestial northern hemisphere |

Common Features:

Same basic techniques used

Overall costs \sim same

Site permits expansion to next-generation size (1 km³)

While both DUMAND and AMANDA are pursuing the Cherenkov light technique, earlier investigations have suggested that a very large volume detector of high energy neutrinos can be constructed at very low cost using acoustical detection. The deposition of energy in the water by produced particles generates a low level characteristic bipolar sound pulse with an effective frequency spectrum peaked in the range 30 to 60 KHz. The hydrophone array built into DUMAND for its positioning system is very efficient in this range, and should be capable of detecting particle cascades of about 1 PeV at a range of 40 m.¹⁹ Simulation studies suggest that by using noise cancellation and signal coherence techniques (i.e., treating our set of hydrophones as a phased array), it will be possible to systematically enhance noise rejection and detect high energy particles. The DUMAND array will be equipped to observe coincidences of OM and acoustical signals, and this will provide the first direct practical test of acoustical detection. DUMAND will also supply acoustical equipment to AMANDA for tests of acoustical detection in the ice.

Throughout the process of detector construction and deployment, the two groups have engaged in mutual assistance and cooperation despite the inevitable sense of competition. It is quite likely that at some point in the future, we will be working together directly to focus resources and expand capabilities. The present DUMAND and AMANDA arrays, even after all currently planned deployments are completed, will serve primarily as test beds and prototypes for a much larger detector.

5 The Next Step: Km³

Both the DUMAND and AMANDA groups acknowledge that detectors with effective areas on the order of 10^4 m^2 provide marginal capability for detecting neutrino sources given present theoretical estimates as well as data on gamma rays. The aim of the present generation of detectors, including Baikal and NESTOR, is to demonstrate the value of neutrino astronomy by providing the first look at the neutrino sky. Definitive results will be likely to come from the next generation of neutrino detectors, which must have sensitive volumes on the order of a cubic kilometer. Given the history of DUMAND, with a delay of nearly 30 years between the first discussions of the detector concept and its materialization in hardware, everyone with an interest in neutrino astronomy is concerned about re-

ducing the lead time for the next step. In part, during the early years DUMAND was a concept waiting for the development of appropriate technology, e.g., wet-mateable fiber optics connectors, which became available in the late 80s), but it is certainly not too early to begin design and organizational activities on the second generation now.

It seems clear that both the deep-sea and polar-ice approaches have valuable features as well as problems that are not yet resolved, at least to the satisfaction of the community at large. At present, it is still possible that AMANDA will find no end to its bubble problem at practical depths. Similarly, although the basic feasibility and technological issues are resolved, it is essential for DUMAND to definitively demonstrate its ability to overcome component reliability problems and operate a complex detector system deep underwater on a long-term basis. If either group fails to achieve these goals, the direction for future work will be clear; in the happy circumstance that both detectors work as planned, a decision about whether the km³ detector should be underwater or in the ice will be based on assessment of results from initial runs.

Several significant initiatives took place in early 1994: a workshop held at the Jet Propulsion Laboratory led to the formation of a U.S.-based coalition to pursue a cubic kilometer detector, and later the European Community's Megascience Workshop resulted in a similar European coalition. At the 1994 Snowmass Summer Study (entitled "Particle and Nuclear Astrophysics and Cosmology in the Next Millenium"), an interest group combining both coalitions was organized. The existing BAND groups (Baikal, AMANDA, NESTOR, DUMAND) are working with the JPL group and others to organize workshops aimed at preparing a conceptual proposal before the end of 1995, so that funding initiatives can begin promptly. Already, JPL workers have begun development of new OM designs which have extremely low power consumption and use optical fibers for power as well as data transmission. Interested individuals should join the group to keep apprised of progress; consult the World Wide Web for further details:

<http://web.phys.washington.edu/km3.html>

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