Neutrino Astronomy with Large Cherenkov Detectors

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Abstract

The present status of experiments and prospects for future high energy neutrino astrophysics endeavors employing Cherenkov radiation detection are summarized. Economics almost surely dictate the employment of massive water (or ice) Cherenkov detectors in the next decades in beginning neutrino astronomy since present and near-future underground experiments may not be large enough to detect point sources of neutrinos. Roughly 6 third generation detectors (in the $>10{,}000$ m^2 class) are in various stages of proposal, test or construction, some of which will come to operation by the mid-nineties. The DUMAND II detector, now in construction for deployment in Hawaii for operation beginning in late 1993, is described in some detail. Several novel detection techniques, particularly for application in the Antarctic, are briefly discussed, and prospects for the future examined. For the present it seems that water (or ice) Cherenkov detectors employing photomultipliers remain the most cost effective means to reach the 1 km^2 sizes needed for neutrino astronomy in the next generation.

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I Neutrino Astronomy and Cherenkov Detectors

Physicists have dreamed of starting neutrino astronomy since the mid '60s[1]. Nobody questions the importance of neutrinos in cosmology, in that neutrinos outnumber protons by 10^9 or so, and in that if neutrinos have only a small mass (>30 eV, summed over flavors) they may dominate the mass of the universe. Unfortunately no practical plans have been put forward to detect these relic neutrinos, so we must begin with the much more easily detected and surprisingly abundant higher energy neutrinos. For example, more cosmic ray neutrinos exist at the earth's surface and below, at all energies, than any other (free) particle of similar kinetic energy (eg. high energy muons). The miniscule interaction crossection for neutrinos, down by about 14 orders of magnitude from gamma rays at 1 GeV, drives one to think about detecting higher energies.

One might attempt to 'see' the universe in neutrinos produced by nuclear processes, in the 10 MeV range. Unfortunately, though stars produce huge fluxes of neutrinos due to nuclear burning, we have had a very hard time even detecting our own sun (see the various papers summarizing the "solar neutrino problem" at this meeting[2]). Detecting stellar fusion neutrinos from point sources beyond our solar system (or even the aggregate of many sources, as from the whole galactic nucleus) seems unlikely (and for which terrestrial reactors would provide a significant background).

However, the tremendous burst of neutrinos from gravitational stellar collapse (GSC) should be fairly easily detectable from throughout our galaxy. The dramatic observation of supernova SN1987A by IMB[3] and Kamiokande[4], yielded about 10 events above 10 MeV in 1000 tons of Cherenkov detector from a distance of 50 kpc (the LMC). The rate of Type II supernovae in our galaxy being no more frequent than one in 10 to 50 years[5] (and quiet GSC not much more frequent than once every few years), one would like to observe neutrinos from our galactic cluster. Recently there has been renewed interest in the possibility for a detector of a few megatons effective volume, massive enough to sense events out to a few Mpc, detecting roughly one supernova per year[6]. We will not discuss that initiative further here, but will focus upon the detection of higher energies where beginning neutrino astronomy may be easier, and probably will be realized earlier.

The attraction of utilizing natural bodies of water for achieving the necessary megatonnage needed to begin neutrino astronomy has long been obvious. The least expensive of bulk materials, say concrete, cost of the order of US$25–50/ton. Even (reverse osmosis or micropore) filtered water costs this much if one includes the cost of the filtration plant, plumbing, and container. While the costs of deploying detectors in the deep ocean, deep lakes or polar ice may be higher than in a laboratory situation, these differences tend to become smaller as the scale of the detector grows.

In general the surface arrays must pay a penalty of high civil engineering costs and greater photocathode coverage per unit area (in order to beat the fierce downward flux of muons, dominating the upward muon flux by 10^{12}), while receiving the benefit of accessibility. The net photocathode penalty of working at the surface is about a factor of two compared to deep detectors, but when further accounting for effective solid angle of the array, surface Cherenkov detectors require about 6 times the photocathode area per unit solid angle area for neutrino detection.

The advantage of a Cherenkov detector in contrast with a scintillation counter or tracking counter is simply that the expensive part of the apparatus need not intercept the track and only occupies a small fraction of the track sensing area. In Monte Carlo simulations for many different geometries of deep ocean muon detectors we have found that one needs about one (40 cm diameter) photomultiplier per 100 m^2 of total array effective area, or about 0.0012 fractional projected photocathode area, largely independently of geometry of the array. At a typical large photomultiplier cost of roughly $\$2.5/cm^2$, this translates to $\$18/m^2$ of array effective area. One may compare this cost with a cost of a few hundred dollars per square meter for any kind of ordinary counter that intercepts the track (X–Y, at least two planes).

One may wonder if photomultiplier tubes (PMTs) can be improved upon for detecting the Cherenkov light. As yet, solid state detectors remain too expensive and noise limited. Gas photocathodes, as employed in ring imaging Cherenkov detectors at accelerators, seem quite possibly useful when coupled to grid multiplier structures. So far these chambers have only have been developed with gases that have sensitivity in the UV below about 200 nm; for use in water the sensitivity would need to be in the 300 – 500 nm range.

Another approach, improving traditional PMTs by coupling them to wavelength shifters may yield collection gains in the range of a factor of two. However this improvement was explored and rejected by the DUMAND group (mainly for mechanical reasons) and was not very successful for the IMB–2 detector (increases noise and smears timing). Reflectors may help enclosed detectors, and have recently been added to the Kamiokande detector. (However, a cylindrical reflecting surface, in the short lived HPW detector in the Silver King mine in Utah, made event reconstruction nearly impossible.)

One may also consider radiation in other parts of the electromagnetic spectrum. Only the radio frequencies have reasonable transmission distances in solid media. Because Cherenkov radiation depends upon sign, most of the radiation from a particle cascade cancels out. The coherent signal power (depending upon the square of the net radiating charge excess) arises mainly from electrons around the periphery of the cascade by Compton scattering. Recent calculations[7] indicate that the energy threshold for detection of a cascade at 1 km is discouragingly high, probably above 5 PeV in the best of conditions (good geometry, thermal noise limited).

The only other (identified) potentially useful long range natural radiation which might be utilized to detect muons or cascades at a distance arises from the acoustic pulse produced by rapid heating of the medium traversed by ionizing particles[8]. The kilometer attenuation lengths of sound in water make tempting the idea of using hydrophones to achieve gigaton detector sizes, except for the catch that the practical detection threshold appears to be in the range of 10^{16}eV.

Thus one is hard pressed to beat the use of natural water (or ice) and the employment of Cherenkov detection by PMTs for construction of the enormous detectors needed to begin neutrino astronomy. Yet one has no guarantee that this will always be the most cost effective technique, and particularly not beyond the extremes in high ($>10^{16}$eV) and low energy (<10 MeV) considerd herein.

The DUMAND group has long recognized that the best beginning for neutrino astronomy is likely to be in the TeV neutrino regime, via the use of Cherenkov detection of muons from ν_μ charged current interactions[9]. Since the νP cross section rises with energy, the muon range increases with energy, the angle between the neutrino and muon decrease with energy, and the cosmic ray neutrino background is more steep ($E_\nu^{-3.6}$) than expected sources (E_ν^{-2}), we expect that the signal-to-noise gains strongly with energy. The rationale for anticipating flat neutrino spectra is fairly broadly based[10], coming independently from observations in gamma rays, acceleration models, and the relation to the cosmic ray spectrum (and we have no example model for a steep neutrino spectrum). Folding these factors together, the time required to detect a given source falls with increasing muon threshold energy, out to an energy in the range of 100 GeV to 1 TeV[11]. Depending upon the flux level, one soon runs out of signal, so further raising of the threshold is not useful. Hence a detector sensitive to >100 GeV muons is desirable, which corresponds to neutrino detection in the TeV range (for the hypothesized flat spectrum neutrino sources).

Given that TeV neutrino detection may be the best for beginning neutrino astronomy, one must face the crucial design question of how large a muon detection area is needed to get into business? There have been calculations of neutrino flux based upon energetics of celestial objects[10], but all they really demonstrate is that detectable fluxes, even with existing underground detectors, are allowed (but not required). We do have one way to calculate lower limits on possible neutrino fluxes with reasonable reliability, and that is via the observations of very high energy (VHE, TeV energy range) and ultra high energy (UHE, PeV energy range) gamma rays. It is generally believed that at least the UHE gammas are beam dump products (that is γ's from π° decay), not electromagnetic in origin. The somewhat delicate requirement of a target thick enough to make gamma rays, but not so thick as to absorb them (10 – 100 gm/cm^2), makes it seem *a priori* unlikely that one would see any gamma rays.

Nevertheless, if one accepts the (now disputed) VHE and UHE γ observations, one can predict lower limits on the associated neutrino fluxes. Typically the ν/γ flux ratio is expected to be 1 – 50 considering time variation. Existing underground neutrino detectors in the range of 100 to 1000 m^2 of muon counting area could potentially detect such point sources. They have not yet done so, and since flux sensitivity will only increase as the square root of time, it seems unlikely that present generation instruments will discover point neutrino sources unless a burst should be observed.

Many possible sources of neutrinos do not have accompanying gamma rays[10], however. Neutrinos may come from the decay or annihilation of relic particles, associated with the "missing mass" problem. Neutrinos may come from beam dump situations where the target matter is sufficiently thick to kill the associated gamma rays. And, one of the most interesting prospects are neutrinos from γP interactions wherein the photons from subsequent π° decay are thermalized by $\gamma\gamma \rightarrow e^+e^-$ in the dense photon fields surrounding a compact object. A new model by Stecker, Done, Salamon, and Sommers[12] makes predictions for neutrino fluxes that exceed the cosmic ray background above about 20 TeV from the integral over all active galactic nuclei (AGNs). This flux would result in thousands of >10TeV muons/year in DUMAND II, which events would be distinguishable from the cosmic ray neutrino background by energy alone[13]. In fact there should be an equivalent ν_e flux such that even direct resonant (6.4 PeV) $\nu_e e^- \rightarrow W^-$ production may be observable (order of 10 events/year contained in DUMAND II at the nominal Stecker, et al. model flux).

The best current data set for point source neutrino searches, via upcoming muons observed in the IMB detector[14], shows tempting visual correlations with the highest peaks with the galactic plane which however are not statistically compelling.

Hence it seems that detectors one or two orders of magnitude larger than present instruments in area, and with an order of magnitude higher muon energy threshold, may be necessary to detect the first neutrino point sources. However, it has been long recognized that probably a full 10^6 m^2 will be needed to really begin regular neutrino astronomy[15].

II Survey of HE Neutrino Cherenkov Detectors

The first natural neutrinos were observed in scintillation and flash tube detectors located in deep mines in South Africa[16] and in India[17] in the mid-sixties, and the larger of them, CWI, collected about 100 events. Another experiment in Utah collected a few events[18]. The first experiments did not have very good directionality, and for most events one could only deduce the projected direction. The energy threshold was low as well, in the 100 MeV range, so that one could not hope to do much with point source astronomy. Nevertheless these experiments made the first atmospheric neutrino flux measurements, and did set the first limits on extraterrestrial neutrino fluxes[16,17].

Little activity in the field took place for about a decade, until the search for proton decay became fashionable, in the late seventies. Since the early eighties 8 large detectors have operated, 6 of them continuing, and several more are in various stages of proposal, feasibility testing, or construction (see Table I). The two biggest detectors were, and still are, the IMB and Kamiokande water Cherenkov instruments, which have been spectacularly successful in applications from a few MeV (eg. solar neutrinos in Kamiokande) to searches for all manner of higher energy exotica, most prominently nucleon decay, for which these collaborations have reported most of the strongest limits.

The 90's will see the completion of several new underground detectors, such as MACRO[19] and LVD[20] in Italy, SNO in Canada[21], and SuperKamiokande[22] in Japan, so that there will be about 9 ongoing experiments underground through the middle of the decade, as summarized in Table I. Three of them employ the water Cherenkov technique (IMB, SNO and SuperKamiokande). Because these detectors approach the maximum stable mine cavity size, much larger underground detectors appear unlikely.

The prospects for other large neutrino detectors, as indicated in Table II, are less clear. We can divide the new $>10^4$ m^2 initiatives into two classes: surface and underwater (or ice). Detectors located on the earth's surface such as GRANDE[23], LENA[24] and NET[25], aim at using a covered pond for studying upcoming muons from neutrinos. The detection, as in the deep water detectors, is via the

Cherenkov radiation of particles in water, the light being sensed by large downlooking photomultipliers. Surface detectors may also study extensive air showers (EAS) with a layer of upward facing PMTs in the same detector (though curiously NET does not include uplooking PMTs). An exception to the use of Cherenkov radiation in the surface neutrino detector category is the SINGAO proposal[26] which would employ novel resistive plate chambers. The second category is characterized by deep water Cherenkov detectors employing open natural bodies of water, generically of the DUMAND type, with strings of PMTs floating upwards from bottom moorings.

The underwater approach is being pursued by the international DUMAND collaboration in Hawaii[27], about which more below, and also by other groups in the USSR[28] and Europe[29,30]. The Soviets have a substantial ongoing program in Lake Baykal in Siberia[31]. Another group has been carrying out tests for an ocean based DUMAND style instrument, possibly for emplacement in the Mediterranean[32].

In looking at Table I one should be aware that deep underearth detectors (which can look for neutrinos arriving from slightly above the horizon) have a solid angle advantage of about a factor of 3 over flat surface arrays (which must restrict their viewing region to below 20° below the horizon), so that area comparison alone is misleading.

III DUMAND Hawaii

The DUMAND organization got started with a series of workshops in the mid-to-late seventies, with the goal of building a very large under-ocean detector. This stimulated the first serious considerations of types of neutrino experiments, venues, energy ranges, and techniques. The best location was soon realized to be in the abyssal deep off Hawaii. Since the early '80's the collaboration has been engaged in studying the environment and backgrounds, developing the necessary technology, and carrying out system design studies. A prototype experimental demonstration was carried out in 1988, measuring muon fluxes in the open ocean from depths of 2 – 4 km. The group received US DOE approval in April 1990, to proceed with a long term ocean bottom moored array, which is scheduled for full operation in late-1993 at total project cost of about US$10M.

The design goal for DUMAND II[9] was for a deep ocean moored instrument with 20,000 m^2 of muon area and an angular resolution of 1°. The configuration arrived at is a 100 m diameter octagon of strings, with a ninth string in the center. These strings will float upwards from a 4.8 km deep ocean bottom, about

30 km off the Island of Hawaii, at 19° 44′ N, 156° 19′ W. Each string consists of 24 optical modules, plus laser calibration units, hydrophones (5 per string), and environmental monitoring instruments. The strings will have instrumentation beginning 100 m off the bottom, optical detectors every 10 m for 230 m above, and a float package at the string top, some 350 m off the bottom, to provide tension to keep the strings near vertical in the small ocean bottom currents.

Signals from the PMTs will be digitized to 1 ns accuracy at the base of each string and multiplexed onto a single 625 Mbd fiber optic link for each string. The strings attach to a junction box, which has other instrumentation including TV and lights, and links to shore via a 12 fiber cable which also delivers 5.5 kW to the array. On shore digital signal processors filter out interesting events for on-line reconstruction. Fast data links to collaborating institutions will permit remote monitoring and control, as well as simultaneous data distribution.

An experiment has been proposed to employ the intense neutrino beam from the planned Fermilab Main Injector to study neutrino oscillations via muon neutrino disappearance enroute to DUMAND[33]. While convincing Fermilab to invest in the 30° downward neutrino beamline will certainly be difficult, the physics to be done is quite unique because the typically 20 GeV ν_μ's will have the possibility to experience significant matter oscillations in traversing the 6000 km distance to DUMAND[34]. For an optimal $\delta m^2 \approx 0.01$ ev^2, DUMAND II would observe a measurable deficit out to a (surprisingly small, due to resonance) mixing angle of $\sin^2(2\theta) \approx 0.02$[34], if the oscillation goes from $\nu_\mu \rightarrow \nu_e$.

IV New Approaches and Future Prospects

Beyond the third generation high energy neutrino detectors discussed above, several prospects have appeared for the farther future, as listed in Table II (which should be regarded with due caution). These include employment of microwave radiation from UHE showers in ice (RAMAND), acoustic detection in the ocean, and the possibility of employing Cherenkov radiation in the deep clear antarctic ice.

One must go to the antarctic in order to find ice with a long enough attenuation length to make microwave neutrino detection possible because the attenuation in ice at the relevant frequencies (>300 MHz) only approaches km distances for temperatures below −60° C, as found near the Soviet Vostok Station. The Soviet team has conducted tests for several years, and some U.S. groups have now taken an interest in the possibility as well. However, it remains to be demonstrated that the noise background is low enough and that the technique is practical.

Acoustic detection had a short lived period of activity about a decade ago, but was largely dropped when it was realized that there was probably no way to get the threshold down from 10 PeV to the TeV region where at least atmospheric neutrino signals are known to exist. Some Soviet workers have continued work on the idea, and reportedly will make an experiment in the Atlantic in 1991[35]. The DUMAND group has kept the idea alive as a background operation to the practical purpose of acoustic surveying of the array geometry, and they are now considering the prospects for detecting resonant W^- in the neighborhood of the DUMAND II array. The flash of Cherenkov light from a 6.4 PeV cascade may be seen for several hundred meters, and the arrival time of the acoustic pulse could give the vertex location, thereby permitting event energy determination. Whether this actually will work remains to be determined.

Another novel method for attempting neutrino astronomy in antarctica involves the use of Cherenkov radiation in the ice. An initiative named AMANDA[36], now getting underway in active field study, plans to place PMTs in three 1 km deep holes at the South Pole in the Winter of 1991–1992. Beyond the obvious attraction of working from a solid surface and simply melting holes in which to place the PMTs, albeit in a difficult environment and inaccessible location, a most intriguing aspect of the proposal is that there should be no optical background in deep clear ice. If one neglects the cost of infrastructure at the South Pole (fuel costs to melt the holes, for example), the technique may be economically attractive as well, though the difference between deep ocean and deep ice in technical difficulty may not be much in the end. This author believes that the major advantage of a deep ice detector may be in the (hopefully) negligible optical background, and thus an advantage in building a major supernova detector with few MeV sensitivity and multi–megaton effective volume.

All of the above mentioned new detection techniques are, unfortunately, probably a few years from practical application. Even if realized, the threshold energy may be very high for the microwave technique and the acoustic techniques. Active exploration of the optical technique in ice has just begun, and we need to understand the environment (optical characteristics of ice, depth for bubble free ice, verification of lack of optical background, etc.) before realistic plans for a large detector can be put forward, which could take place within several years[36]. Hence it appears that the competitors for beginning very high energy neutrino astronomy through mid–decade will be (some of) the Soviet and Hawaii DUMAND detectors, the GRANDE and SINGAO style detectors, and perhaps an AMANDA detector at the South Pole. It is a healthy situation for there to be several such instruments, and with various techniques employed. The first signals are not likely to be large, so independent confirmation will probably be necessary (and usually teaches one something).

Beyond the mid–90's we need to begin to contemplate the next step, which on a logarithmic scale suggests a 1 km^2 detector. While such a device will almost surely not be realized before the turn of the millennium, it is certainly not too soon to begin to work on the means to achieve such an instrument. The author presently favors an extension of the DUMAND approach, which does scale well to great size, requiring about 10^4 modules (PMTs) and roughly US$100M. While this represents a reasonable cost scale by present day accelerator standards, it will probably require a substantial international collaboration to obtain the necessary resources.

However, in order to proceed with such grand visions we must have success in detecting the first astrophysical point sources of high energy neutrinos in the shorter term. Indeed the physics might point in other directions, which we cannot now know. Perhaps also, new technology will come along that will make other techniques more attractive. We must continue exploring detection technology, and most important, make the upcoming generation of instruments work as well as planned. For now, it appears to this author that the simple Cherenkov detection technique, employing natural bodies of deep ice or ocean and photomultiplier tubes, will be hard to beat.

Acknowledgements

The author would first like to thank the Brighton meeting organizers for a stimulating meeting. I want to thank all the DUMAND collaborators for the work of theirs upon which I have drawn so heavily for this report. I must say also that the material about other experiments reported upon herein may well be wrong, particularly in reference to those detectors in the proposal stage, about which I have used preliminary and in some instances guessed numbers. Nevertheless, the scale of things presented herein (in Table II in particular) are about right, but one should be careful about inferring anything other than overall trend.

Footnotes and References

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27) The DUMAND Collaboration consists of groups from Aachen, Bern, Boston, Hawaii, KEK, Kiel, Kinki, Kobe, Okayama, Scripps, Tohoku, Tokyo, Vanderbilt, Washington and Wisconsin.

28) There appear to be at least 3 separate groups working on DUMAND type of neutrino detectors in the Soviet Union. One, headed by V.I. Domogatsky and L. Bezrukov is in Baykal (see Ref. 31 below), another by I.M. Zheleznykh and N.M. Surin aims toward a detector in the Mediterranean or Atlantic, and a third group under A.A. Petrukhin is directed at a device in the Pacific. The former two groups are from the Institute of Nuclear Research in Moscow, the latter from the Moscow Engineering Phys. Inst.

29) NESTOR is a project proposal headed by L.K. Resvanis of the U. Athens, Greece, with a detector proposed for Med. waters off SW Greece.

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