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DUMAND and Other High Energy Neutrino Astronomy Projects

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Abstract

High energy neutrino astronomy at last seems to be nearing reality, after decades of speculation and preliminary experimental work. This review (preview) summarises the anticipated types of sources, energy regime for first attempts, scale size needed, and techniques. A summary of 12 relevant current proposals and projects for $> 10,000m^2$ muon collecting area instruments is presented, with emphasis on the first of these probably to be realised, DUMAND II. By the end of the decade there are likely to be several such new generation instruments in operation. The business of high energy neutrino astrophysics will, hopefully, be underway by the turn of the century.

1. Energy Range and Sources

Much effort has gone into the exploration of ideas and techniques for detecting Big Bang relic neutrinos, stellar neutrinos, and supernova neutrinos. As things stand no practical way to detect the relic neutrinos[1] has yet been found. So also with stellar neutrinos from other than our Sun[2], and supernova neutrinos from beyond the immediate neighborhood of our galaxy (not even out to the nearest starburst galaxies at $\sim 3Mpc$)[3, 5, 4].

Without belaboring the subject, it has been obvious to many for some time now[6] that the easy road to neutrino astronomy runs at high energies, and via the observation of the long range muons resulting from charged current neutrino interactions in the TeV energy range. Almost everything improves with energy: cross section ($\propto E_\nu$, until around $10TeV$ and then $\propto log(E_\nu)$); muon range ($\propto E_\mu$, until around $1TeV$, then $\propto log(E_\mu)$); solid angle into which the particles from a point source are scattered by the weak interaction ($\propto 1/E_\nu$); and also, most probably, the inherent signal-to-background ($\propto E_\nu^{\sim 1.4}$). The latter is due to the fact that the spectrum of the terrestrial cosmic ray neutrinos is steeper than the primary cosmic rays by one power of the energy (due to competition between decay and absorption of mesons in the atmosphere), and that the neutrinos probably reflect the spectrum near the source of the cosmic rays, while the cosmic ray spectrum is steepened in transit by increasing leakage from the galaxy at high energies. In any case, though all the above favor higher energies, the inevitable decrease of flux with energy makes one settle on the energy range above $1TeV$, where backgrounds for achievable detectors become small.

The following paragraphs categorise the sources that have been discussed for such high energy neutrinos thus far[7].

1.1. Cosmic Beam Dumps

Most consideration has been given to the simple model of neutrino production from a cosmic beam dump, conceptually like those at accelerators, where a proton (or heavy ion) beam impinges on a target, producing secondary particles (mostly pions) which then decay to gammas, neutrinos, and charged particles. In the probably rare instance when the target is just thick enough to produce π^0s and not so thick as to absorb γs ($\sim 5-100gm/cm^2$), we may observe the γs on earth. In almost all imagined cosmic circumstances the target density is not enough to absorb the pions or muons (typically $< 10^{-8}gm/cm^3$) prior to decay, and, except through the cores of stars, the column density is unlikely to be great enough to absorb any significant fraction of the neutrinos produced by decay of those pions and muons[8]). Since the production and transport of neutrinos is far more robust, *ab initio* one should expect more and stronger neutrino sources than gamma ray sources of such origin to be visible to us.

Many calculations have been done for the galactic objects from which there are claimed detections in TeV and PeV gamma rays, and these generally indicate potential observability with next generation instruments (see Section 2 below) [12]. Some favorite galactic objects are X-ray emitters such as Her X-1, Cyg X-3, 4U0115+63, Sco X-1, Vela X-1, LMC X-4, Cen X-3, Cir X-1, LMC X-4 (in the Large Magellanic Clouds $50kpc$ distant, not quite in our galaxy). Most have temporal structures identified on time scales from seconds to years, associated with neutron star rotation period, binary orbital period and perhaps longer precessional periods. The picture formed from many observations involves an accretion driven lighthouse-like beam of particles emitted by the neutron star (or black hole), which beam impinges upon the accretion disk, local cloud of matter, or limb of the companion star. Considerations of observed photon luminosity[10] restrict the likely galactic detections in the near future to supernova shocks, young pulsars, X-ray, and hidden sources (eg. a Thorne-Zytkow object[9]).

A similar type of neutrino source arises from the photoexcitation of protons and neutrons to states (eg. $p + \gamma \rightarrow \Delta^+$) which then decay back to nucleons plus pions, thence to gammas and neutrinos. This process may occur not far from the Schwarsschild radius of a giant black hole in a galactic nucleus (AGN), where particle acceleration occurs via the Fermi mechanism in the infalling material at the standing accretion shock. The photons cascade via $\gamma\gamma \rightarrow e^+e^-$ to lower energies (and upwards in number density, to order of $10^{14}/cm^3$) providing a dense photon target that quenches the proton acceleration as it approaches the Δ resonance in the proton rest frame (at $E_p \sim 10^{16}eV$ in the lab frame) . This mechanism may serve to explain several facets of observations in UV, X-rays, and of the broadened stellar spectra from such galactic nuclei. Moreover, the AGNs may thus also be the long sought source of the highest energy cosmic rays[16].

There is no doubt that such objects show fantastic luminosity in the electromagnetic spectrum ($10^{45-47}ergs/sec$). While the presence of a black hole is not certain, no other explanation seems to suffice, and so the gravitational infall makes about 10% of the mc^2 energy potentially available as fuel. The magnetic fields are not known, but can be guessed from arguments of equipartition (kG), though this is perhaps the most controversial area of quantitative model building for these objects.

The result of several such AGN neutrino production models indicates the possibility of observing neutrinos of energies up to $\sim 10^{16}eV$[13, 14]. Indeed, amongst a half dozen different models as examined at a recent workshop[14], there was agreement within a factor of about five in predicted event rate despite widely varying assumptions[15](see rate predictions for

DUMAND II below in Section 4.1.1).

A peculiarity of this class of objects is that they seem brighter and more numerous farther away. So, while individual AGNs may not be detectable in next generation instruments, the ensemble may (due chiefly to the distinctive flux at PeV energy, see 3.3 below). Further excitement has been added to this area by the recent GRO observations of GeV gammas from Active Galaxies, and the surprising observation of Markarian 421 by the Whipple group at 1 TeV in gamma rays[19]. Perhaps shockingly, this observation implies that the greatest part of the luminosity of Mk421 is in the unconventional region of astronomy above TeV photon energies. Interestingly, there are no corresponding TeV detections of more distant GRO sources, which may well be attenuated by $\gamma - \gamma$ interactions on the intergalactic infrared over the vast flight distance[17]. Beaming, the nature of the production of γ's in this Blazar, and the magnitude of the magnetic fields, make definitive prediction of the neutrino flux difficult. Inferred underearth muon fluxes for Mk421 range from near zero to values that should already have been observed[18].

The potential for neutrino observation of AGNs has several striking consequences. For one thing, the energies are high enough to incur significant attenuation of the neutrino flux while traversing the earth (attenuation length about one earth diameter at $E_\nu = 1PeV$), and thus make possible, in principle, study of the earth by neutrino tomography (in some future generation instrument)[20]. Of more immediate consequence, as discussed for DUMAND II below (Section 4.1.1), a significant flux at 6.4 PeV can make the observation of resonant $\overline{\nu}_e + e^- \rightarrow W^-$ detectable in an instrument that can view a sufficiently large target volume ($\sim 10^8 tons$).

1.2. Neutrinos from Terrestrial Accelerators

We shall not dwell upon the possibilities for neutrino oscillation searches utilising neutrino telescopes, but simply note that there have been a number of studies and proposals for long baseline experiments[21]. None have yet been approved, mostly because the beam line requirements for detectors at large distances are quite costly. Also, at large distances (1000 km) the rate becomes a problem for all present scale underground detectors. While the new generation of instruments will have the size needed for distant detection, the threshold tradeoffs made to achieve great size become troublesome (eg. DUMAND II will have a threshold of around 10 GeV, whereas one would like to go down to about 1 GeV if employing the new Fermilab Injector). Yet another difficulty is the recognition of the appearance of tau neutrinos (really a problem in almost all but extremely fine grained emulsion experiments), not practical for large detectors. The best sensitivity can be achieved for searches for muon disappearance, and by normalisation to neutral current events one can escape the problems of systematic uncertainties in the source neutrino flux. The parameter of interest, L/E, that one can achieve with such experiments is not easily matched, even by proposed long distance reactor experiments. Should the oscillation be dominantly from muon-like neutrinos to electron-like neutrinos, then a detector such as DUMAND II located at $6000km$ from Fermilab could be sensitive to matter effects. I would suppose that when the new generation detectors come into operation, and if the topic is still interesting, we will see such experiments approved and they will make important contributions to this area [21].

1.3. Atmospheric Neutrinos

The neutrinos generated in the earth's atmosphere by interaction of the primary cosmic rays at energies above a few GeV consist of mostly muon neutrinos and anti-neutrinos, because such muons seldom decay in flight. (The present anomaly from Kamiokande and IMB of the ν_e/ν_μ fluxes observed as compared to expected, is in events where one expects the ratio to be about 1/2, with energies between $100MeV$ and $1GeV$[22].) Based upon the well measured muon fluxes, one can thus employ the absolute rate (though with difficulty) and angular distribution of these neutrinos to search for muon neutrino disappearance. This has been done already with underground instruments, but they are limited in statistics. This and the difficulties in normalisation restrict the results to mixing angle limits $sin^2(\theta) \geq 0.1$. The new generation instruments will be able to extend this somewhat, with deeper instruments at an advantage not only in size but also by being able to employ the flux near and even above the horizon.

Of course the atmospheric neutrino flux is also both detector calibration for astrophysical source hunting, and background to it. The atmospheric neutrinos are much more soft in energy than the expected flat spectrum ($1/E^2$) sources, with anticipated mean energies from the two types at least an order of magnitude different ($100GeV$ for atmospheric neutrinos, and $1TeV$ or more for cosmic sources).

1.4. Cosmological Sources

This category includes neutrinos from the many rather speculative potential sources, the observance of any of which would have fundamental significance. An example is neutrinos due to particle acceleration around superconducting cosmic strings[23]. Other sources are from the early universe, the tip of the cosmic ray spectrum (the Zatsepin-Greisen cutoff), decay of relic particles, and even Planck mass objects called cosmions (see [25] for a review). A characteristic of most such models is extremely high energy neutrino emission, but also low fluxes at more accessible energies. Detectors of the highest energy cosmic rays are well suited for finding these phenomena (and limits have been set by the Fly's Eye experiment, for example). If such fantastic phenomena do exist, then techniques such as acoustic and radio detection, discussed below, may have an important role to play in studying them. However, these sources do not appear to be candidates for detection in the detectors now under consideration.

1.5. WIMPS

Much effort has gone into the detection of dark matter candidates in various mass and kinetic energy regimes[11]. The neutrino telescopes can make contributions in the search for heavy (many GeV) mass particles which become trapped in the earth or sun, and which eventually annihilate with their anti-partners similarly trapped, producing great numbers of particles, including neutrinos which then escape the core. Experimentally the search is straight forward, searching for a muon excess in the direction of the earth's core or of the sun. While a great amount of parameter space has already been eliminated by underground experiments and LEP, the new generation instruments will make significant improvements because of both greater sensitivity (larger area) and sensitivity to higher masses (higher neutrino energy thresholds) [26].

2. How Large a Detector is Needed?

Of course this is *the question* most critical to experimentalists, and to funding agencies. The sensible approach, acknowledging that we really do not know, would be to build bigger detectors, taking steps on a logarithmic scale, until we get into business. Because of the existence of UHE cosmic rays (up to $10^{20}eV$ or so), we know that the neutrinos are there at some level, but where? Lacking any firm ground, people have tried three approaches: upper bounds based upon total observed system luminosity in photons, scaling from gamma ray observations, and speculative model building.

There does seem to be a consensus amongst astrophysicists who have thought about the issue that the range needed is somewhere from just beyond the present size of underground detectors ($< 1000m^2$) to around $100,000m^2$. The conservative experimentalist would aim for a full $1km^2$. Unfortunately that seems to be too great a step from existing practice and budgets, so the next few years will see detectors in the $10^{4-5}m^2$ range, and we hope for the best. In the following we first discuss the background, and then discuss the achievable sensitivities for point sources and diffuse sources. That is followed by an illustrative point source calculation based upon the observed energetics of a galactic object (Her X-1). Later we present results of calculations for a $20,000m^2$ muon collecting area detector, which indicate that for the AGN models recently discussed, the sum of all AGNs should be detectable soon.

2.1. Terrestrial Backgrounds for Astrophysical Detection

The terrestrial background for high energy astrophysical neutrino detection is neutrinos from cosmic ray interactions in the atmosphere, as discussed above. The angular distribution of this flux is shown in Figure 1., where we see that it peaks near the horizon, due to the greater chance for pions to decay when entering the atmosphere at a grazing angle. The spectral index of the atmospheric neutrinos is about -3.8 above a few GeV, which leads to relatively low mean energies for the muons, particularly at an underearth detector where the mean muon energy is about 20 GeV (this to be compared with TeV mean energies of muons from expected cosmic sources).

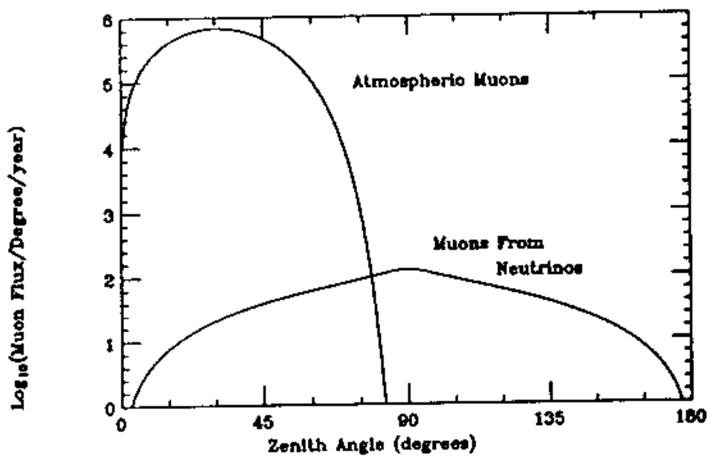

Fig. 1. Angular distribution of cosmic ray muons from the surface and from neutrino interactions for a 5 *kmwe* deep experiment[11].

The cosmic ray muons, siblings of the neutrinos, penetrate even the deepest mines and overwhelm the neutrino signal in much of the upper hemisphere. There is a slow gain by going deeper, in that one can resolve the neutrino signal over a larger solid angle. For example at $5kmwe$ depth the neutrinos dominate up to about $10°$ above the horizon, while for surface arrays, the limitation for neutrino detection is from about $20°$ below the horizon downwards, a difference of a factor of 1.8 in solid angle.

Another factor is the number of downgoing muons, which presents the danger of misreconstruction of downgoing tracks as upgoing and false identification as neutrinos. This is a serious issue for arrays at the earth's surface because the up-to-down ratio is about 10^{-12}: predicting the reliability of event reconstruction via computer simulation fails under weight of numbers. It is for this reason that the surface arrays must have a higher density of detection elements than deeper detectors, thus offsetting some of the advantages of working at the surface versus mines, ocean or polar ice. However, even the deep arrays must seriously face this problem, since they take advantage of the quieter conditions to deploy more sparse arrays. Multiple muons, which are present in the downgoing flux at about 2% of the single muon flux are a special problem for possible misreconstruction in this regard (though interesting as a subject for study in themselves).

This discussion assumes that completely bogus (noise generated) events have been removed. In deep ocean instruments one has to be concerned about the random association of photomultiplier pulses (almost all single photoelectron) generated by ocean radioactivity and bioluminescence. The experimentalists can assess this background, and set the detection threshold accordingly, so that what survives analysis are *bona fide* muons: it is only a matter of cost, or detector effective area penalty, depending on how one wishes to characterise it, a restriction routinely incorporated in the detector design.

As discussed in the following, cosmic ray neutrino produced muons do not pose a serious background problem for the new generation of detectors, though they have been a limiting factor for mine based experiments with low muon energy threshold.

2.2. *Point Source Detection*

Point source detection has been the primary goal in initiating neutrino astronomy. The typical neutrino source will have a relatively flat spectrum, as discussed above, and this will result in a point spread function that is not gaussian about the source direction, but more sharply peaked, with higher energies nearer the center. The angular spread is dominated by the weak interaction, magnetic fields and electromagnetic scattering being relatively small, with a typical angle of about $1.5^\circ/\sqrt{E_\nu/TeV}$. This has set the angular resolution scale for the new generation instruments at about 1°.

Note that if a source is observed, one can do better than the individual event resolution in determining the centroid of the distribution, so it is important to push the detector surveying to go beyond the event resolution by an order of magnitude or so. Also, if very high energy sources such as AGNs are detectable individually, then the higher energy muons from these (with mean energies of order $10TeV$) would be better resolved (at least in Water Cherenkov detectors), and one may get event resolutions approaching 0.1°.

Figure 2. illustrates the muon energy dependence of the signal-to-noise ratio for a "typical" point source, showing the strong advantage having a higher threshold, up to about $100GeV$ to $1TeV$, because while the background falls swiftly, little is lost of the hypothetical signal. The total background one is working against depends upon size and this threshold. For illustration, DUMAND II expects about 3500 muons per year from atmosperic neutrinos above 50 GeV in energy. The directions of these neutrinos will be distributed fairly uniformly in the sky (with some declination dependence), and divide amongst the roughly 10,000 equivalent pixels to be searched at 1° resolution.

Thus for such size detectors one will not be bothered with terrestrial backgrounds if one sets a threshold of 6 or more for point source discrimination threshold. Further tests on a suspected source can confirm the detection by testing the angular and energy distributions of the events in the peak. One can also look for spatial correlations with objects known by other means, and for temporal modulations (which are rather likely if the objects are X-ray binaries for example).

The net expected point source sensitivity for a $100GeV$ neutrino energy threshold, 20,000 m^2 detector deep underearth, is about $10^{-10}\nu/cm^2/sec$ with energy above $1TeV$. This flux is close to the levels claimed by VHE γ detectors.

2.3. *Diffuse Source Detection*

Diffuse sources, such as the galactic disk or the ensemble of distant AGNs are another matter however. Here we cannot dismiss the atmospheric background. In the case of the galactic plane we can compare the total flux in that direction with that from the rest of the sky, as is done regularly in studies of extensive air showers. This requires some care as the mapping of the background atmospheric neutrinos onto the galactic coordinates is not isotropic. Estimates of the detectability of the normal galactic neutrino flux due to interactions

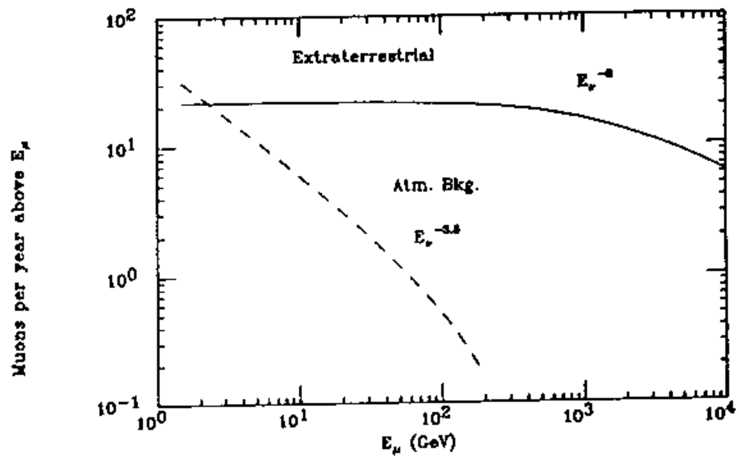

Fig. 2. Typical expected point source signal and cosmic ray neutrino background versus muon energy at the detector[11].

of the cosmic rays with the galactic dust and gas are not very encouraging for next generation instruments[12].

A more difficult problem is discerning a nearly isotropic distribution, as say from galaxy formation or from the sum of all AGNs. Here we are left with only three tools identified so far. First we can look for energy spectrum differences between the observed flux and that predicted for the cosmic ray neutrinos. This will not work well for subtle differences, but should suffice in the case of the currently popular AGN models, as illustrated in Figure 3., where one sees that the atmospheric flux would be well separated by an energy cut of $10TeV$ on the muons. A more difficult, but still possibly effective, discriminant is the difference in angular distributions.

Detection of the particle cascades downstream of the neutrino interaction, rather than the muons alone, provides another method for finding a diffuse source. For deep ocean, and perhaps deep ice (depending upon ice transparency), instruments, it may be possible to "see" events at ranges of hundreds of *meters*. The anticipated energy distribution of particle cascades in an energy dependent volume (of about $0.2km^3$ of water at $6.4PeV$, scaling roughly as $(logE_{cas})^{3.7}$, as predicted for DUMAND II[15]), is shown in Figure 4. for four different models. The total number of events would be between 52 and 264 events per year above 100 TeV deposited energy, where the predicted atmospheric background (neglecting direct production) is 5 events per year. Cascades do not seem promising for point source detection in next generation instruments because cascade direction resolution probably is not adequate.

One may also try more esoteric data analysis techniques to attempt to discern statistical characteristics of a cosmological flux buried in the atmospheric noise. For example, the known clustering of galaxies would also be reflected in the clustering of neutrino directions from that class of galaxies which produce them. One can employ some of the same techniques developed by astronomers in searching for galactic clumping. One obvious technique is to employ the two point correlation function on the neutrino sky map. The atmospheric neutrinos in the sample will not have any correlation with either themselves or the putative cosmic neutrinos, but the cosmic neutrinos will show positive correlations at small angles, and the angle scale of the correlation reveals something of the nature of the sources. Higher moments can be studied too. The statistics needed for these studies will probably require detectors beyond the next generation.

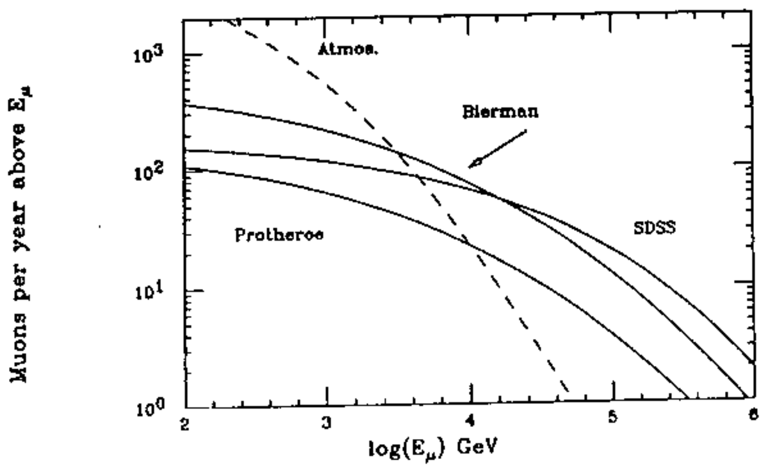

Fig. 3. Predicted energy distributions for muons from AGN, and for atmospheric neutrinos. The calculation is for DUMAND II, including slow increase from nominal $20,000m^2$ area for low energy muons[14].

2.4. *An Estimate of Event Rate: Why New Detectors Needed*

We can do a trivial calculation of the counting rate of a detector based upon the observations of Her X-1, an X-ray binary about which we know the geometry rather well and which has been the source of several peculiar high energy phenomena[28]. The object has claimed luminosity of $L_\gamma \simeq 3 \times 10^{35} ergs/sec$ in TeV gammas, at a distance of $R_s = 5kpc$. If we take the nominal detector area to be $A_\mu = 20,000m^2$ then the equivalent target volume is about $V = 2.5km \times A_\mu = 5 \times 10^7 tons$ for $1TeV$ neutrinos. With a cross section of $\sigma^{cc}_{\nu_\mu N} = 6 \times 10^{-36} cm^2/nucleon$, and $N_0 = 6 \times 10^{29} nucleons/ton$, we get a total effective target area of $180cm^2$ for neutrinos of this energy. The gammas are modulated with the orbital motion of the system, and if the production is off the limb of the companion Hz-Her star then neutrinos are made with much higher duty factor than gammas. Models give factors of 1 to 1000 for the increase in neutrino flux; we will take $\nu/\gamma = 50$ for illustration. Finally the detector will not be on all the time, nor have the source in its field of view continuously (except for detectors at the Poles, whose field of view does not change), so we take a typical efficiency of $\epsilon = 1/2$.

The rate prediction in this simple calculation is then:

$$R_\mu = 5 \times \left(\frac{\nu/\gamma}{50} \frac{\epsilon}{0.5} \frac{A_\mu}{10^4 m^2} \frac{L_\gamma}{3 \cdot 10^{35} ergs/sec} \right) \cdot \left(\frac{5kpc}{R_s} \right)^2 \; events/year. \qquad (1)$$

This is a naive calculation but gives approximately the same results as more sophisticated efforts. The conclusion we can draw is that, if indeed these objects are making gamma rays at the suggested intensities, then it seems likely that the neutrinos will be detected in the next generation instruments, but that they are just beyond the reach of the existing underground detectors[24].

3. Techniques

In order to achieve the huge sizes needed for high energy neutrino astronomy it appears that some natural radiation from the interaction must be employed to give one some area gain in catching the disturbance. The traditional approach, as at an accelerator, would be to completely cover a given area with some sort of active detector. To demonstrate the

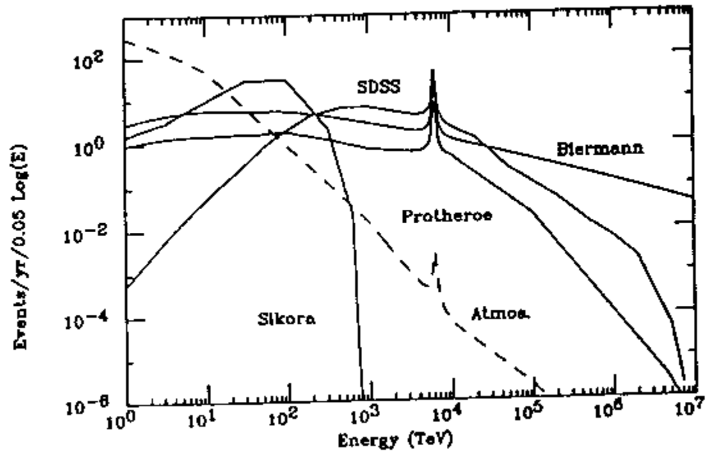

Fig. 4. Predicted cascade event spectrum from AGN, and from atmospheric neutrinos for DUMAND II[11].

Table 1. Various techniques proposed for use in large neutrino detectors.

Radiation	Medium	Active	Detect Muon	Detect Cascade	Energy Threshold	Atten. Length	Detected Spectral Region
Cherenkov	Air	Y		Y	$100GeV$	$10km$	$200-500nm$
	Filtered H_2O	Y	Y	Y	GeV	$>10m$	$300-500nm$
	Natural Lake	Y	Y	Y	GeV	$\sim 10m$	$400-500nm$
	Deep Ocean	Y	Y	Y	GeV	$\sim 40m$	$350-500nm$
	Polar Ice	Y	Y	Y	GeV	$\sim 25m$	$400-500nm$
	Radio	Y		Y	$>5PeV$	$\sim 1km$	$0.1-1GHz$
Acoustic	Water	Y		Y	$>1PeV$	$\sim 5km$	$10-20kHz$
	Ice	Y		Y	$>PeV$	?	$10-30kHz$
	Salt			Y	$>PeV$	?	$10-50kHz$
Shower	Air	?		Y	$10PeV$	1 km	$100MeV$

impracticality of this for high energy neutrino telescopes let us assume we want a detector of area 10^5m^2, and that we need 3 XY layers, with absorber, at a cost of $\geq US\$\ 10K/m^2$, for a total cost of order $US\$\ 10^9$!

The techniques are summarized in Table 1., where one may observe that, remarkably, almost all of are being actively pursued. All the techniques suggested for mammoth detectors have relied upon some natural radiation with a transverse component, mainly Cherenkov radiation. One variation employs air shower detection, looking for near horizontal showers, where one gets the area gain by intercepting some of the secondary particles of the cascade in the atmosphere. Another category of techniques employs the acoustic pulse produced by expansion of the medium when heat is deposited by the particle cascade, an inefficient process with energy transfer efficiency in the range of 10^{-9}.

Cherenkov radiation is peaked towards the blue, generally being cut off in the UV by Rayleigh scattering. The clearest known natural waters are in the deep oceans, where the transparency approaches that of distilled water, with attenuation length maximum of around $40m$ in the region of $450nm$. Natural lakes seldom are better than about $10m$ and suffer from seasonal variations. Surface detector arrays must filter their water, adding significantly to the engineering cost (though they only need about $10-15m$ water). Antarctic ice optical properties have not yet been measured *in situ*, but laboratory measurements suggest an attenuation length of $\sim 24m$, and preliminary counting experiments suggest that scattering is not a a great problem[29].

Radio detection of particle cascades suffers also from high threshold. Here the problem is simply that most of the low frequency Cherenkov radiation from the particles cancels out since the radiation formula is

$$\frac{dW}{d\nu} = \frac{4\pi\hbar\alpha}{c} Z^2 \nu [1 - \frac{1}{\beta^2 n^2}] l \; , \tag{2}$$

but unfortunately $Z = \Sigma q \simeq 0$. Still there is some radiation because the particle distribution has asymmetries (due to the difference in scattering of electrons and positrons, and the Compton scattering of photons from electrons in the medium). Another problem is the propagation of the electromagnetic waves. The Antarctic provides a unique environment, having ice pure enough and, most importantly, cold enough for reasonable transmission of the radio waves. The resulting cascade detection threshold for a range of $1km$, under ideal noise conditions, appears to be $\sim 5PeV$[30].

The acoustic detection technique has the great attraction that the attenuation length for sound in water is in the range of km for frequencies of interest, $10-20kHz$, and fortuitously the noise in the deep ocean also is at a minimum in this same energy regime. Moreover the technology of acoustic sensing and processing is well developed. The problem is that the signal is so small that the detection threshold is likely to be in the PeV range[31]. One may also contemplate acoustic detection in solid media, but the medium must be very homogeneous, and have no cracks. The two examples considered have been salt domes and deep ice (both of which are self annealing). Deep ice is now being studied[32], but salt domes are not. We shall discuss this further below under specific projects.

4. Summary of Projects

In the following we briefly review the dozen or so projects now underway in high energy neutrino astronomy. The past, present and future (proposed and underway) projects are listed in Tables 2. and 3..

We will not say much about the older instruments, which were not designed expressly for neutrino astronomy. One sees from Table 2. that there are two fairly well defined generations of instruments. The first, built in the '60s were aimed simply at making the detection of natural neutrinos, though of course one of the goals was to see if there were strong extraterrestrial sources. The next group started about 10 years later, boosted to funding by the possibility of detecting nucleon decay, as predicted by the $SU(5)$ theory. Some of these instruments continue to operate. The most successful were the IMB and Kamiokande detectors, which had the great fortune to observe the burst of neutrinos from SN1987A, the beginning (and end, so far) of extra solar neutrino detection. The present world total of neutrino induced muons with energy $> 2GeV$ is ~ 2000, mostly from IMB, Baksan and Kamiokande. No obvious sources have appeared in those data, and limits have of course been extracted, but are not yet restrictive of any models[33]. Naturally if one looks hard at the data set one can imagine hints, but the statistics are not strong enough to make any claims. Note that all the underground instruments have a low muon energy threshold making the signal-to-noise about a factor of ten worse than equivalent size detectors with a 20 GeV muon energy threshold.

Another group of underground detectors are in operation or under construction for next generation nucleon decay searches, monopole search, solar neutrino studies, and supernova watch (with heavy overlap in capabilities of the instruments)[34]. These low energy threshold (MeV) instruments will however probably not make much progress in high energy neutrino astronomy because they are simply not big enough in area, and so represent somewhat of a sidebranch in the taxonomy of neutrino telescopes.

Table 2. Summary of large underground instruments with high energy detection capability, 1960's through mid 1990's.

Detector, Location	Status	μ Area (m^2)	Directon Sense	Technique	Primary Purpose
KGF, South India	X	10	N	LS + FT	obs νs
CWI, South Africa	X	110	N	LS + FT + Fe	obs νs
Silver King, Utah	X	30	Y	WC + Ctrs + Fe	obs νs
KGF, South India	X	20	N	ST	PDK
Baksan, Caucasus	R	250	Y	LS tanks	νs
IMB, Ohio	X	400	Y	WC	PDK
HPW, Utah	X	100	Y	WC	PDK
Kamioka, Japan	R	120	Y	WC	PDK
NUSEX, Mt. Blanc	X	10	N	ST + Fe	PDK
Frejus, France	X	90	N	ST + Fe	PDK
Soudan I, Minnesota	X	10	N	ST + Concrete	PDK
Soudan II, Minnesota	R	100	N	DT + Fe	PDK
MACRO	R	800	Y	LS + ST +	monopoles
LVD	C	500	Y	LS tanks + ST	SN νs
SNO	C	300	Y	D_2O WC	solar νs
Superkamioka	C	740	Y	WC	PDK
Borexino	T	<100	Y	LS	solar νs

Key for Table:

P = proposed	T = testing	WC = water Cherenkov	ST = streamer tube
C = construction	R = operating	LS = liquid scintillator	PS = plastic scintillator
X = shut down		FT = flash tubes	

4.1. *Water Cherenkov Detectors*

The water Cherenkov type of detectors, pionereed in the '80's by IMB and Kamiokande in deep mines, have had the most attention for obvious economic reasons. These instruments divide into the surface detectors and those at substantial depths. The surface arrays have the advantage of accessibility and the option to study downcoming air showers as well as looking for upwards moving neutrinos. The penalties are heavy civil engineering cost (for a covered pool and water filtration), dense detection elements (required to thoroughly reject downgoing events), and a restricted solid angle. The deep water detectors must cope with the pressure, difficulty of service, and unwanted background light (as from K^{40} decays in the ocean). Deep ice has different unique advantages and problems, discussed below under AMANDA.

4.1.1. *DUMAND II*

The DUMAND Project in Hawaii is the grandfather of these efforts, having been active for more than ten years (though with first workshops going back to 1975!) defining the problems, doing the background studies needed, and creating the technology necessary for working in the deep ocean. Construction is now underway for a nine tethered-string instrument, roughly $350m$ tall and $106m$ in diameter, and consisting of 216 optical modules, plus 14 laser calibrators, environmental monitoring (tilt, heading, temperature, salinity, pressure, TV), and 52 hydrophones. The optical modules are spaced $10m$ apart over $230m$ height, with 8 strings spaced $40m$ in an octagonal pattern, with one string and a junction box in the array center. The effective area for muon detection is about $20,000m^2$, and the volume inside the

Table 3. Summary of new initiatives in high energy neutrino astronomy.

Detector	Location	Status	μArea ($10^3 m^2$)	Solid Angle ($/2\pi sr$	Depth (mwe)	Technique	Threshold (GeV)
Baikal NT-200	Siberia	C'94	3	0.83	1000	WC	10
DUMAND II	Hawaii	C'93	20	1.17	4760	WC	20
NESTOR	Greece	T/C	100	1.15	3500	WC	1
AMANDA	Antarctic	T/P	100	0.83	1000	WC in ice	20
SINGAO	S. Italy	T	15	0.66	10-0	RPC	2
LENA	Japan	T/P	30	0.66	0-30	WC	6
GRANDE	Arkansas	P	31	0.66	0-50	WC	6
NET	Italy	P	90	0.66	0-70	WC	11
Blue Water Project	Australia	D	100	0.66	0-60	WC	10
PAN	Sweden	P	100	0.66	0-40?	WC	10
SADCO	Greece	T	1000	1.0?	3500	Acoust	$> 10^6$
RAMAND	Antarctic	T	1000	1.0?	1000	μwv	$\sim 10^6$
World Detector	?	D	1000	1.2?	>4000	WC?	>100?

Key for Table:

P = proposed (possible operational date) WC = water Cherenkov
T = testing and development RPC = resistive plate chamber
C = construction (operational date) μwv = microwave detection
R = operating Acoust = acoustic wave detection

open cylinder is about $2 Megatons$. The threshold energy is about $20 GeV$ for muons, and the response for contained cascades is very crudely $1 PE/GeV$. Individual OM counting rates are expected to be $60 kc/s$, and the downgoing cosmic ray muon rate to be about $3/min$.

The effective volume for $6.4 PeV$ resonant W^- cascades is about $2 \times 10^8 tons$ because of ability to view UHE events at several hundred meters in the clear deep ocean water. This is a unique capability to the deep ocean detectors, since surface arrays have fixed visible volume, and the deep ice experiment will apparently not have such a large seeing range. The expected rates to be observed in DUMAND II for various AGN models as are listed in Table 4., where one sees that if these models are correct we will not only be able to detect this diffuse source of neutrinos, but begin to discriminate amongst models[15].

Table 4. The number of muon and cascade events per year expected in DUMAND II from AGNs according to various models presented at the workshop in Hawaii in March '92, and for atmospheric neutrinos[14].

Source	$E_\mu > 100 GeV$	$E_\mu > 10 TeV$	$E_{cas} > 1 TeV$	$E_{cas} > 100 TeV$	Model
Sum of AGNs	154	66	276	264	SDSS
	109	23	113	52	Protheroe
	366	75	379	172	Biermann
	897	148	680	125	Sikora
Atmosphere	2950	23	3435	5	Volkova

The experiment will have (shore based) triggers to record muons, cascades, supernovae, slow particles (eg. nuclearites), and bipolar acoustic pulses. The supernova detection will assuredly not be very likely, but could provide confirmatory detection for a nearby galactic event via an increase in the multi-pe counting rate in optical modules over several seconds[36].

It is expected that the fiber optic cable will be laid from the 4760m deep site to the shore station 30km distant on the big Island of Hawaii in mid-1993. The first 3 strings will be placed and connected employing a submarine soon thereafter. This crucial deep ocean connection operation was practiced successfuly at the DUMAND site in October 1992. The remaining 6 strings are scheduled for deployment in mid-1994[35].

4.1.2. Lake Baikal

The Baikal group has also been laboring for many years to place a detector in deep water, but in this case the fresh water of 1.4km deep Lake Baikal. They take advantage of the annual freezing of the surface to work from a solid platform, lowering instruments through holes in the ice, and laying cables to shore through a slot cut by a huge saw towed on a sled. The water is not as clear as the ocean, and surprisingly an optical background has been found in the lake water which is similar in magnitude to that produced by the K^{40} in the ocean (about 200 $detectable\ quanta/cm^2/sec$), but variable with season. The 1km depth of the instrument leads to difficulties in the rejection of downgoing muons, forcing the detectors to be more densely packed and resulting in less effective area per module than would be the case for deeper locations. The photomultipliers are in clusters of four, and have local coincidence circuits. This group employs the Philips XP2600 15 inch tube, and a Russian equivalent, the QUASAR tube. The Baikal group has however, suffered from lack of available technology, and at present, given the difficulties in the former Soviet Union, it is not clear how well things will proceed. The plan has been to operate the NT200 array, with 48 clusters of detectors and an effective area of about 2000m^2 in about 1995[37].

4.1.3. NESTOR

The NESTOR Project is the relatively new entry into this field. It includes a group from the Institute of Nuclear Research in Moscow, a group from Athens, Greece, and now Italian physicists. The Greek collaborators have funding to set up a laboratory in Pylos, in the South West of Greece, and conduct the intial stages of the project. They hope to get a small array working by '94, with a large array (of order $10^5 m^2$) in about 1996. The situation is evolving with the collaboration still growing, and the construction timescale as yet flexible. The Russian group has had a few years of experience in extended ocean tests, and have already counted muons to 4km depth working with the Greeks. Their style of detector is rather like an umbrella with the modules placed at the ends of the 7m (later 10m) spines, which unfold when the cluster is submerged. A single 400m string of these will form a "tower", and a cluster of towers a full $10^5 m^2$ array[38]. A difference in this geometry and DUMAND is that NESTOR will try for better low energy sensitivity. NESTOR's location, 177° in Latitude away from DUMAND makes for complimentary sky coverage.

Extensive site studies were carried out in November 1992, following up on work over the last two years, and these confirm the excellence of the location (good bottom, excellent 40m water transparency, low currents), with 3.5km deep water only 14km distant from a light house to be utilized as shore based counting station. An informal workshop in Pylos, contemporaneous with this conference, generated substantial interest in Europe[38].

4.1.4. JULIA

JULIA is yet another proposal for a deep ocean instrument, largely the effort of Peter Bosetti and students at Aachen. The special characteristics proposed for JULIA are to have a three layer nested instrument with inner low energy section (10MeV), moving out to a layer tuned for GeV events, and an outer envelope of high energy sensitivity $(5 - 10TeV)$. Some work has been carried out in site studies in the Canary Islands and detector module prototyping[39].

4.1.5. AMANDA

The AMANDA project, aiming to put neutrino detectors in the clear deep ice at the South Pole, has generated a great deal of interest of late. Below several hundred meters in depth the ice is bubble free due to pressure. Because of the isolation from world weather flow, the ice is as pure as distilled water.

The advantages of such an experiment are that one can work from a solid base, putting the photomultipliers and a minimal amount of electronics down a hot water drilled hole, and employ fairly standard triggering and recording electronics. It seems that the PMTs must be frozen into the hole and are irretrievable once deployed. There are also limitations on the hole diameter, preventing the use of 15 inch PMTs, and limiting the hole depth (due to fuel costs). An infrastructure exists to provide the access to the polar station and to do the drilling with no direct cost to the project. Funding for initial tests has been obtained, and a three string array will be installed in 1993-4. The effective area and depth will be similar to Baikal NT200[29].

Note that another advantage of the polar ice is the lack of optical background, which may ultimately make it a good location for a low energy (MeV) detector. If the attenuation length in ice is really $24m$, as compared with the $40m$ of the deep oceans, this implies a limitation upon cost effective large arrays in ice.

4.1.6. GRANDE

The GRANDE Collaboration was the first to seriously study and propose a large surface array (plans were maturing in Japan for LENA about the same time though) employing a shallow pond with photomultipliers looking up and down to be able to study both upcoming neutrinos and downgoing EAS. This group derived the parameters now confirmed by similar studies for NET and PAN, that the PMT lattice spacing should be $\sim 6m$, there should be $\sim 10 - 15m$ between planes, and that three planes constitute the mimimum number needed. The limit in horizontal area is only due to economics, but the civil engineering costs are high. It appears that a $100,000m^2$ detector can be built in the US for about $US\$ \ 40M$, in an existing quarry in Arkansas[40].

The GRANDE proposal was initially put on hold, but the proponents have not conceded yet, though they have joined with the Italians in the NET proposal.

4.1.7. LENA

LENA is somewhat different in proposed geometry than GRANDE, but has similar characteristics. A prototype instrument has been operated in Lake Motosu, not far from Mt. Fuji in Japan, and has demonstated that the rejection factors needed for such experiments can be achieved in practice[41]. A lake deployment has the advantage of not having to construct or sculpt a pond, but involves other problems in mooring the light tight bag and PMT support structure, a potentially serious problem in a storm.

4.1.8. NET

An Italian group from Padova and other institutions in Italy has now been joined by Japanese, Americans, French and Swiss in proposing a 10^5m^2 GRANDE style detector for placement near the Gran Sasso laboratory in Italy[42]. The proposal was formally submitted to the INFN in April 1992, and requests a total of about 1.4×10^{11} *It. Lire* $\simeq US\$ \ 100M$. Of this about 63% is for civil engineering costs, which may apparently be obtainable from sources outside the science budget. The proposal is quite developed in terms of engineering, plotting out a full 6 year construction schedule, which would put the detector on the air no earlier than 1998.

4.1.9. PAN

A Swedish collaboration has been considering the possibilities for making another GRANDE style of instrument, but in one of the many clear lakes in Northern Sweden[43]. The same remarks apply as for the other detectors above. It seems that there is Swedish interest in joining the AMANDA effort, a natural for them given their experience with cold climate.

4.1.10. Blue Lake Project

A group from the University of Adelaide has proposed another GRANDE style of detector for a volcanic lake in Mt. Gambier, South Australia[44]. While it seems quite attractive to have such a detector in the Southern hemisphere, it appears that the proposal is on hold due to lack of resources.

4.2. Surface Counter Arrays

As mentioned earlier, counter arrays have generally been thought to be too expensive for a high energy neutrino telescope, and there is only one entry in this category.

4.2.1. SINGAO

The SINGAO group have been exploring the use of resistive plate chambers for a surface array[45]. Probably RPCs are the least expensive counters per unit area, and they have excellent time resolution as well. The idea is to develop them for industrial production and make them in vast quantities inexpensively. However, the high costs of structures and absorber needed between layers cannot be escaped, and though the RPCs may be fine for an EAS array they probably will not be a contender for an neutrino telescope in the $10^5 m^2$ class.

4.3. Radio Detection

Like most other ideas, this has been around many years, but the dauntingly high energy threshold has deterred most people from doing the development work needed.

4.3.1. RAMAND

Another Russian INR group has been actively pursuing a program to study the noise temperature in the deep ice at the Antarctic Vostok Station, where the ice is $-56°C$[46]. They have operated an array of 7 antennas placed 15m deep, and found an equivalent noise temperature of $1500°K$, though it is expected to be lower deeper into the ice. There is an optics problem, with the index of refraction increasing down to about $100m$ depth. Because the ice becomes warmer with depth the attenuation length decreases with depth. The net result is that at Vostok station the UHE cascade detection range is limited to about 1 km (for 1 GHz).

The Russians have proposed an array of 330 antennas to be in place by 1996, for which they claim a S/N of 3 at 1 km for 1 PeV. Again the economic upheavals in the former USSR call this plan into question.

4.3.2. Other

Several other groups have talked about similar activities at the South Pole, and some doing cosmic microwave background studies at the Pole have turned their antennas downwards to measure noise tempertures from the ice[50]. I know of no serious program similar to RAMAND as yet.

4.4. Acoustic Detection

Acoustic detection has been talked about since the late 1970's, and experimental work took place in the US and USSR. In particular an American group measured acoustic pulses in water at Brookhaven in 1978, finding that the temperature dependence was largely as predicted by the thermo-acoustic mechanism, except for an unexplained tripolar pulse present at the temperature of greatest density of water ($4°C$)[47]. In any case the experimental results and calculations pointed to a threshold energy for detection of the order of PeV or more[31], so the idea was dropped in favor of Cherenkov detection. With the new AGN models suggesting the availability of interactions of such energy at levels of possibly many per year in a km^3 volume of water there has been a revival of interest.

4.4.1. SADCO

The same Russian INR group as involved with NESTOR has been working steadily for a few years to develop an acoustical array, which they call SADCO[48]. They plan three initial $100m$ strings, with 384 hydrophones total, $100-200m$ apart, for deployment with autonomous recording packages in '93 - '95. They claim a threshold of $6PeV$ over $10^9 m^3$. Note that the Mediterranean is much warmer than the oceans, with the tempreature at $3.5km$ depth near Pylos being $14°C$, helping with the threshold by a factor of three over the deep ocean.

4.4.2. Acoustic DUMAND

The DUMAND group has kept the idea of acoustic detection alive, ever since the activity more than a decade ago[47], but on a secondary track. Hydrophones are to be used for on-line surveying of the array position in DUMAND II, to take account of the small swaying of the array (few meters at the top) in the tidal motions of the water in the deep basin. For this purpose there are to be 5 hydrophones per string, each having digitisation at $100KHz$ sent to shore for analysis by a digital signal processor. While the deep ocean high frequency noise is not yet measured, it is expected to be near thermal above $10KHz$. If there are indeed substantial numbers of cascades of energies in the PeV region, as suggested by current AGN models, then DUMAND may have the opportunity to both see and hear such events. While it seems that the 52 hydrophones to be put in the DUMAND II array cannot make a significant acoustic detector in themselves, the practical experience gained will enable the construction of such an array if the science warrants it.

4.4.3. Acoustic AMANDA

Some members of the AMANDA Collaboration are considering the possibility of acoustic detection in the Antarctic ice as well[32]. There are some sure advantages in pulse production, but the attenuation remains unmeasured. A further advantage is that ice, being a solid, supports shear waves[49]. Observing both compressional and shear wave gives range in one record. Experimental tests are required.

5. Conclusion: On the Threshold

As one sees from the number of proposals and actual programs underway, the field of neutrino astronomy seems to be heading for an active future. The DUMAND II project is now nearing operation and it seems possible that 4 major detectors may operate before the turn of the century. With a substantial number of calculations indicating that we are not far from detecting astrophysical objects, it would indeed be surprising if we do not see the birth of high energy neutrino astronomy before the end of the millenium. Seeing the beautiful results from gamma ray and X-ray astronomy presented at this meeting makes me wonder how long it will be before we have such results from neutrinos. I suppose the answer is several decades, but at least we should be finding the brightest objects in the neutrino sky in a few years.

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