Detection of Cosmic High Energy Neutrinos

John G. Learned

Phil. Trans. R. Soc. Lond. A 1994 **346**, 99-110
doi: 10.1098/rsta.1994.0011

Detection of cosmic high energy neutrinos

By John G. Learned

Department of Physics and Astronomy, University of Hawaii at Manoa,
Honolulu, HI 96822, U.S.A.

High energy neutrino astronomy at last seems to be nearing reality, after nearly three decades of speculation and initial experimental work. This review summarizes the experimental goals, energy régime for first attempts, scale size needed, and detection techniques. A short review of past and present underground detectors is followed by a summary of 12 relevant current proposals and projects for > 10000 m^2 muon collecting area instruments. 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 (Smith 1991) has yet been found. So also with stellar neutrinos from other than our Sun (Hampel 1993), and supernova neutrinos from beyond the immediate neighbourhood of our galaxy (not even out to the nearest starburst galaxies at *ca.* 3 Mpc) (Burrows 1992; Becklin 1990; Tammann 1992).

Without belabouring the subject, it has been obvious to many for some time now (Roberts 1976) 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 10 TeV and then $\propto \log(E_\nu)$); muon range ($\propto E_\mu$, until around 1 TeV, 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 favour higher energies, the inevitable decrease of flux with energy makes one settle on the energy range above 1 TeV, where backgrounds for achievable detectors become small.

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

Phil. Trans. R. Soc. Lond. A (1994) **346**, 99–110

Printed in Great Britain

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	100 GeV	10 km	200–500 nm
filtered H_2O	Y	Y	Y	GeV	> 10 m	300–500 nm
natural lake	Y	Y	Y	GeV	~ 10 m	400–500 nm
deep ocean	Y	Y	Y	GeV	~ 40 m	350–500 nm
polar ice	Y	Y	Y	GeV	~ 25 m	400–500 nm
radio	Y	—	Y	> 5 PeV	~ 1 km	0.1–1 GHz
acoustic	—	—	—	—	—	—
water	Y	—	Y	> 1 PeV	~ 5 km	10–20 kHz
ice	Y	—	Y	$>$ PeV	?	10–30 kHz
salt	—	—	Y	$>$ PeV	?	10–50 kHz
shower	—	—	—	—	—	—
air	?	—	Y	10 PeV	1 km	100 MeV

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 among astrophysicists who have thought about the issue that the range needed is somewhere from just beyond the present size of underground detectors (less than 1000 m^2) to around 100000 m^2. The conservative experimentalist would aim for a full 1 km^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.

Due to space constraints in this volume, we refer the reader to the preceding article by Berezinsky, summarizing many possible point and diffuse astrophysical neutrino sources. Below, for the DUMAND detector, we present some results of calculations for a 20000 m^2 muon collecting area detector. Several calculations indicate that for the active galactic nuclei (AGN) models recently much discussed, the sum of all AGNs should be detectable soon.

Detectors of this class will have other physics capabilities, searching for WIMPS, neutrino oscillations, and various speculative phenomena such as nuclearites, quark nuggets, and magnetic monopoles that catalyse nucleon decay.

3. Techniques

To achieve the huge sizes needed for high energy neutrino astronomy it appears that some natural radiation from the interaction must be used to provide 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 impracticality of this for high energy neutrino telescopes let us assume we want a detector of area 10^5 m^2, and that we need three X–Y layers, with absorber, at a cost of not less than US\$10 K 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 uses 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 uses 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 40 m in the region of 450 nm. Natural lakes seldom are better than about 10 m and suffer from seasonal variations. Surface detector arrays must filter their water, adding significantly to the engineering cost (though they only need about 10–15 m water). Antarctic ice optical properties have not yet been measured *in situ*, but laboratory measurements suggests an attenuation length of *ca.* 24 m, and preliminary counting experiments suggest that scattering is not a great problem (Barwick 1993).

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. 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 GHz radio waves. The resulting cascade detection threshold for a range of 1 km, under ideal noise conditions, appears to be *ca.* 5 PeV (Zas 1991).

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, 10–20 kHz, and fortuitously the noise in the deep ocean also is at a minimum in this same energy régime. 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 (Learned 1979). 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 (Price 1993), 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

Table 2. *Summary of large underground instruments with high energy detection capability (1960s–90s)*

(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; DT, drift tubes.)

detector, location	status	μ area m^2	direction sense	technique	primary purpose
KGF, South India	X	10	N	LS+FT	obs *vs*
CWI, South Africa	X	110	N	LS+FT+Fe	obs *vs*
Silver King, Utah	X	30	Y	WC+Ctrs+Fe	obs *vs*
KGF, South India	X	20	N	ST	PDK
Baksan, Caucasus	R	250	Y	LS tanks	*vs*
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+concr.	PDK
Soudan II, Minnesota	R	100	N	DT+Fe	PDK
MACRO	R	800	Y	LS+ST+	monop.
LVD	C	500	Y	LS tanks+ST	SN *vs*
SNO	C	300	Y	D_2O WC	solar *vs*
Superkamioka	C	740	Y	WC	PDK
Borexino	T	< 100	N	LS	solar *vs*

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

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

detector name	location	status	μ area (10^3 m^2)	sol. ang. $(2\pi \text{ sr})^{-1}$	depth mwe	techn.	thresh. 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 Wtr Proj.	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 det.	?	D	1000	1.2?	> 4000	WC?	> 100?

later, boosted to funding by the possibility of detecting nucleon decay as (wrongly) 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 greater than 2 GeV is *ca.* 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 (Becker-Szendy 1991). Note that all the mine located 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) (Beier, this volume). 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.

(*a*) *Water Cherenkov detectors*

The water Cherenkov type of detectors, pioneered in the 80s by IMB and Kamiokande in deep mines, have had the most attention for obvious economic reasons. The new 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.

(i) *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 350 m tall and 106 m 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 10 m apart over 230 m height, with 8 strings spaced 40 m in an octagonal pattern, with one string and a junction box in the array centre. An optical module consists of a glass housing with 15 inch PMT and associated electronics.

The effective area for muon detection is about 20000 m^2, and the volume inside the open cylinder is about 2 Mt. The threshold energy is about 20 GeV for muons, and the response for contained cascades is very crudely 1 PE GeV^{-1}. Individual OM counting rates are expected to be 60 kc s^{-1}, and the downgoing cosmic ray muon rate to be about 3 min^{-1}.

The effective volume for 6.4 PeV resonant $\bar{\nu}_e + e^- \rightarrow W^-$ cascades is about 2×10^8 t because of ability to view UHE events at several hundred metres 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

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 1992, and for atmospheric neutrinos*

source	E_{μ} > 100 GeV	E_{μ} > 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

are correct we will not only be able to detect this diffuse source of neutrinos, but begin to discriminate among models (Stenger 1992).

The experiment will have (shore based) triggers to record muons, cascades, supernovae, slow particles (e.g. nuclearites), and bipolar acoustic pulses. The supernova detection will assuredly not be very sensitive, 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 (Hauptman 1992).

It is expected that the fibre optic cable will be laid from the 4760 m deep site to the shore station 30 km distant on the big Island of Hawaii in the autumn of 1993. The first three strings will be placed and connected using a submarine soon thereafter. This crucial deep ocean connection operation was practiced successfully at the DUMAND site in October 1992. The remaining six strings are scheduled for deployment in mid-1994 (Wilkes 1992).

(ii) *Lake Baikal*

The Baikal group has also been labouring for many years to place a detector in modestly deep water, but in this case the fresh water of 1.4 km 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 $\text{cm}^{-2}\,\text{s}^{-1}$), but variable with season. The 1 km 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 uses the Philips XP2600 15 inch tube, and a Russian equivalent, the QUASAR tube. The plan has been to operate the NT200 array, with 48 clusters of detectors and an effective area of about 2000 m^2 in about 1995. 34 OMs are now installed and counting (Spiering 1993).

(iii) *NESTOR*

The NESTOR Project is a relatively new entry into this field. It includes a group from the Institute of Nuclear Research in Moscow, a group from Athens, Greece, and also Italian physicists. The Greek collaborators have funding to set up a laboratory in Pylos, in the South West of Greece, and conduct the initial 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 some years of experience in extended ocean tests, and have already counted muons to 4 km depth working with the Greeks. Their style of detector is rather like an umbrella with the modules placed at the ends of the 7 m (later 20 m) spines, which unfold when the cluster is submerged. A single 400 m string of these will form a 'tower', and a cluster of towers a full 10^5 m^2 array (Resvanis 1992). A difference in this geometry and DUMAND is that NESTOR will try for better low energy sensitivity and more isotropic muon response. 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 40 m water transparency, low currents), with 3.5 km deep water only 14 km distant from a light house to be utilized as shore based counting station. An informal workshop in Pylos in October 1992, generated substantial interest in Europe (Resvanis 1992).

(iv) *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 (10 MeV), moving out to a layer tuned for GeV events, and an outer envelope of high energy sensitivity (5–10 TeV). Some work has been carried out in site studies in the Canary Islands and detector module prototyping (Bosetti 1991).

(v) *AMANDA*

The AMANDA project, aiming to put neutrino detectors in the clear deep ice at the South Pole, has recently generated a great deal of publicity. Below several hundred metres 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 use 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 due to fuel costs, preventing the use of more than 8 inch PMTs and limiting the hole depth to about 1 km. Fortunately, an infrastructure exists to provide the access to the polar station and to do the drilling (at least initially) without direct cost to the project. Funding for an initial demonstration 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 (Barwick 1993).

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 24 m, as compared with the > 40 m of the deep oceans, this implies a limitation upon cost effective large arrays in ice.

(vi) *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) using 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 *ca.* 6 m, there should be *ca.* 10–15 m between planes, and that three planes constitute the minimum number needed. The limit in horizontal area is only due to economics, but the civil engineering costs are high. It appears that a 100000 m^2 detector can be built in the US for about US$ 40M, in an existing quarry in Arkansas (Adams 1991).

(vii) *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 demonstrated that the rejection factors needed for such experiments can be achieved in practice (Nisikawa 1991). 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.

(viii) *NET*

An Italian group from Padova and other institutions in Italy has been joined by Japanese, Americans, French and Swiss in proposing a 10^5 m^2 GRANDE style detector for placement near the Gran Sasso laboratory in Italy (Moscoso 1992). The proposal was formally submitted to the INFN in April 1992, and requests a total of about 1.4×10^{11} It lire ≈ 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 six year construction schedule, which would put the detector on the air no earlier than 1998.

(ix) *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 (Bergstrom 1992). The same remarks apply as for the other detectors above. Some of this group has joined the AMANDA effort, a natural for them given their experience with cold climate.

(x) *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 (Reid 1991). 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.

(*b*) *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.

(i) *SINGAO*

The SINGAO group have been exploring the use of resistive plate chambers for a surface array (Auriema 1991). 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 a neutrino telescope in the 10^5 m^2 class.

(c) *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.

(i) *RAMAND*

Another Russian INR group has been actively pursuing a programme to study the noise temperature in the deep ice at the Antarctic Vostok Station, where the ice is −56 °C (Provorov 1991). They have operated an array of seven antennas placed 15 m 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 100 m 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.

(ii) *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 temperatures from the ice (Halzen 1990). I know of no serious programme similar to RAMAND as yet.

(d) *Acoustic detection*

Acoustic detection has been talked about since the late 1970s, and experimental work took place in the U.S. and U.S.S.R. 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) (Hunter 1981). In any case the experimental results and calculations pointed to a threshold energy for detection of the order of PeV or more (Learned 1979), so the idea was shelved in favour 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.

(i) *SADCO*

Part of 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 (I. Zheleznykh, personal communication 1992). They plan three initial 100 m strings, with 384 hydrophones total, 100–200 m apart, for deployment with autonomous recording packages in 1993–95. They claim a threshold of 6 PeV over 10^9 m^3. Note that the Mediterranean is much warmer than the oceans, with the temperature at 3.5 km depth near Pylos being 14 °C, helping with the threshold by a factor of three over the deep ocean.

(ii) *Acoustic DUMAND*

The DUMAND group has kept the idea of acoustic detection alive ever since the activity more than a decade ago (Hunter 1981), 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 metres at the top) in the tidal motions of the water in the deep basin. For this purpose there are to be five hydrophones per string, each having digitization at 100 kHz 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 10 kHz. If these 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 (Learned *et al.* 1993).

(iii) *Acoustic AMANDA*

Some members of the AMANDA Collaboration are considering the possibility of acoustic detection in the Antarctic ice as well (Price 1993). 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 (Halzen 1990). 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 programmes 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 four new generation 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 millennium. Seeing the beautiful recent results from gamma ray (GRO) and X-ray (ROSAT) astronomy 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.

Thanks to the many representatives of the various projects who supplied material for this talk, and particularly to my DUMAND collaborators. Also thanks to the organizers of this meeting. This research was supported by US DOE contract DE-AM03-76F00325.

References

Adams, A., *et al.* 1990 GRANDE Proposal, GRANDE 90-005, UCI.

Auriemma, G. 1991 *Proc. 22nd Int. Cosmic Ray Conf.* (*ICRC*), *Dublin, 1991* (ed. M. Cawley *et al.*). HE 5.3.10, **4**, 682.

Bartol, X. 1990 *Astrophysics in Antarctica, AIP Conf. Proc.* **198**.

Barwick, S., *et al.* 1993 *Proc. of 23rd Int. Cosmic Ray Conf., Calgary 1993* (ed. R. B. Hicks) (HE 5.2).

Becker-Szendy, R. 1991 Ph.D. dissertation, University of Hawaii.

Becklin, E. E. 1990 *Proc. Supernova Watch Workshop, Los Angeles, 11/90* (ed. D. Cline).

Berezinsky, V. S., *et al.* 1990 *Astrophysics of cosmic rays*. Amsterdam: North Holland.

Berezinsky, V. S. & Learned, J. G. 1992 *Proc. Workshop on High Energy Neutrino Astrophysics* (ed. V. Stenger, J. Learned, S. Pakvasa & X. Tata). Singapore: World Scientific.

Bergstrom, L. & Johanssan, S. 1992 In *HENA*, *op. cit.*

Bernstein, R., *et al.* 1991 *Conceptual design report: main injector neutrino program*. Fermilab.

Biller, S. 1992 Ph.D. dissertation, UC Irvine.

Bosetti, P. C. 1988 *Observational neutrino astronomy* (ed. D. Cline), p. 249. Singapore: World Scientific.

Burrows, A. 1992 In *Neutrino '92* (ed. A. Morales). *Nucl. Phys.* B (*Proc. Suppl.*) **31**.

De Jager, O. C., Stecker, F. W. & Salamon, M. H. 1992 *Ap. J.* **390**, L49.

DUMAND 1988 *Proposal for a deep ocean neutrino detector*. DUMAND Collaboration, July 1988, HDC-2-88, Hawaii.

Gaisser, T., Stecker, F., Harding, A. & Barnard, J. 1986 *Ap. J.* **309**, 674.

Gaisser, T. 1990 *Cosmic rays and particle physics*, p. 190. Cambridge.

Halzen, F., Learned, J. G. & Stanev, T. 1990 *Astrophysics in Antarctica, AIP Conf. Proc.* **198**, 39.

Hauptman, J. 1992 DUMAND-14-92, Iowa.

Hayashino, T. *et al.* 1992 *Proc. Int. Symp. on Neutrino Astrophysics, Takayama, October 1992* (ed. Y. Suzuki).

HENA 1992 *Proc. Workshop on High Energy Neutrino Astrophysics* (*HENA*) (ed. V. Stenger, J. Learned, S. Pakvasa & X. Tata), *Hawaii, 23–26 March 1992*. Singapore: World Scientific.

Hunter, S. D., *et al.* 1981 *J. acoust. Soc. Am.* **69**, 1557.

Kobayakawa, K. & Samura, T. 1992 *Proc. Int. Symp. on Neutrino Astrophysics, Takayama, October 1992* (ed. Y. Suzuki).

Learned, J. G. 1979 *Phys. Rev.* D1 **19**, 3293. (See references to earlier work by Askaryan & Bowen therein.)

Learned, J. G. & Stanev, T. 1991 *Proc. 3rd Int. Workshop on Neutrino Telescopes* (ed. M. Baldo Ceolin). Venice, p. 473.

Learned, J. G. & Stenger, V. J. 1992 In *HENA op. cit.*

Learned, J. G., *et al.* 1993 Acoustical Detection of Cascades in DUMAND. In *Proc. 23rd Int. Cosmic Ray Conf., Calgary 1993* (ed. R. B. Hicks) (HE 5.2).

Moscoso, L., *et al.* 1992 *NET Proposal to INFN*, Padova.

Nishikawa, K. 1992 *Proc. 4th Venice Workshop on Neutrino Telescopes* (ed. M. Baldo Ceolin) Padova.

Pakvasa, S., Kajita, T., Dye, S., Gaisser, T. & Kasahara, K. 1992 In *Proc. Int. Symp. on Neutrino Astrophysics, Takayama, October 1992* (ed. Y. Suzuki).

Price, B. 1993 Mechanisms of attenuation of acoustic waves in Antarctic ice. *Nucl. Instrum. Meth.* A **325**, 346–356.

Protheroe, R. J. & Szabo, A. P. 1992 *Phys. Rev. Lett.* **69**, 2885.

Provorov, A., *et al.* 1991 *Proc. 3rd Venice Symp. on Neutrino Telescopes*, p. 337.

Punch, M., *et al.* 1992 *Nature, Lond.* **358**, 477.

Reid, J., *et al.* 1991 *22ICRC, Dublin 1991*, HE 5.3.8, **4**, 678.

Resvanis, L. K., *et al.* 1992 *HENA '92*, *op. cit.*, and *Proc. of the NESTOR Workshop, Pylos, Greece, October 92*, *op. cit.*

Roberts, A. (ed.) 1976 *DUMAND Summer Workshop*, Hawaii (Fermilab).

Smith, P. F. 1991 *Texas/ESO-CERN Symp. on Relativistic Astrophysics, Brighton, U.K.* (ed. Barrow, Mestel & Thomas). *Ann. N.Y. Acad. Sci.* **647**, 425.

Spiering, C., *et al.* 1991 Zeuten Preprint PHE 91-013, 12/91.

Stecker, F., Done, C., Salamon, M. & Sommers, P. 1991 *Phys. Rev. Lett.* **66**, 2697; and *erratum* in *Phys. Rev. Lett.* **69**, 2738 (1992).

Stenger, V. J. 1992 *Proc. NESTOR Workshop, Pylos, Greece, October 1992* (ed. L. K. Resvanis).

Tammann, G. 1992 *Proc. Int. Symp. on Neutrino Astrophysics, Takayama, Japan, October 1992* (ed. Y. Suzuki).

Thorne, K. S. & Zytkow, A. N. 1977 *Ap. J.* **832**, 212.

Vazquez, R. & Halzen, F. 1992 Preprint MAD/PH/731 (Madison).

Wilkes, R. J., *et al.* 1992 *Proc. 7th Int. Symp. on UHE Cosmic Ray Interactions, Ann Arbor 6/92* (UWSEA PUB 92-15, DUMAND-9-92).

Zas, E., Halzen, F. & Stanev, T. 1991 In *Proc. 22nd ICRC, Dublin, 1991* (ed. M. Cawley *et al.*), HE 5.3.11, **4**, 686.