DUMAND AND NEUTRINO ASTRONOMY

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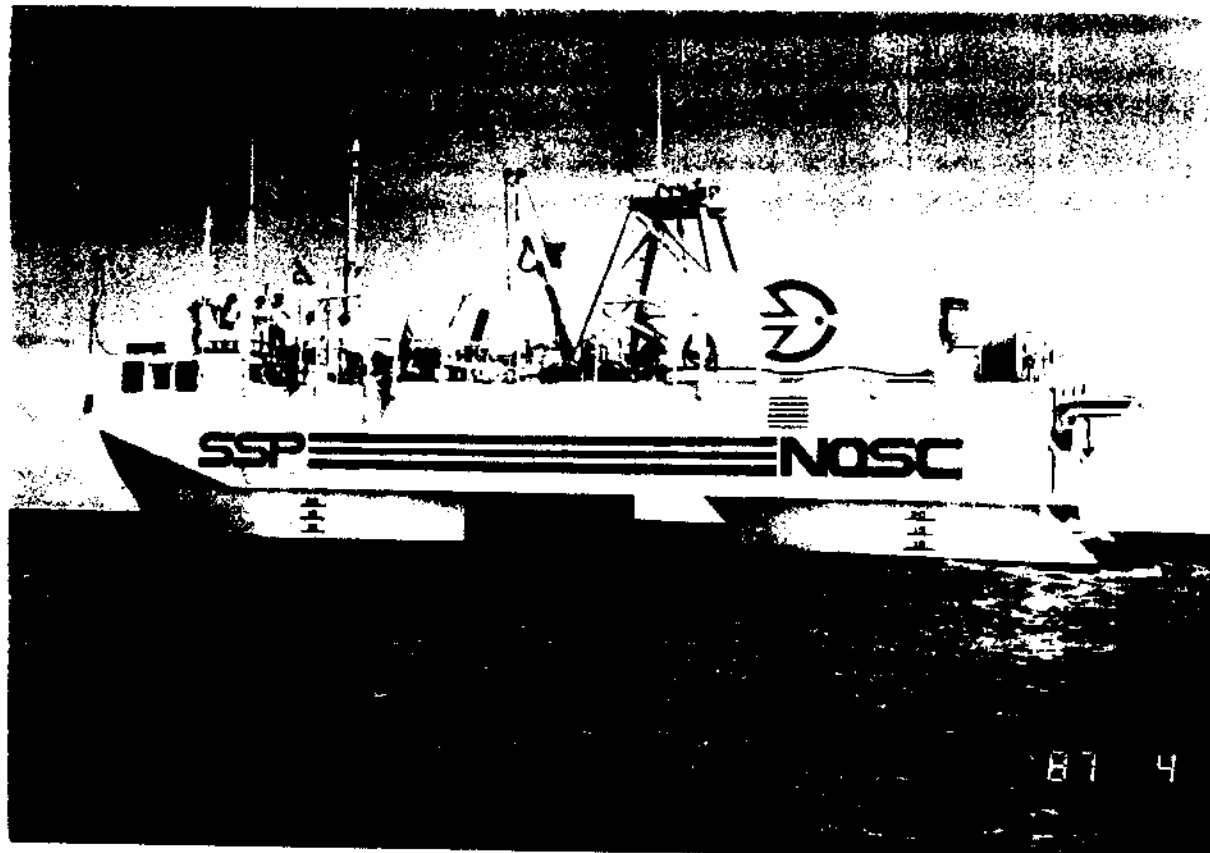
ABSTRACT

The DUMAND project has pioneered in the progress toward neutrino astronomy. Best current knowledge implies that at least 10^4 m^2 detection area is required to detect neutrinos from the most promising sources: binary x-ray systems such as Cyg X-3. This is probably impractical underground, so the DUMAND concept of using the ocean as a detector of very high energy (> 1 TeV) muon neutrinos remains viable. DUMAND has successfully completed its first stage with the deployment of a single string of phototube detectors and the measurement of cosmic ray muons at depths from 2000 to 4000 m. The basic detector units and technology required have been developed, ocean parameters and backgrounds measured and overall feasibility established. Proposals for the next stage are under study.

INTRODUCTION

Over 25 years ago, Markov[1] and Greisen[2] independently proposed that a large area detector placed underground, or underwater in a lake or the sea, would be capable of observing the muons produced by high energy neutrino interactions in the earth, and that these neutrinos could be of extraterrestrial origin. In order to achieve these aims, the Deep Undersea Muon and Neutrino Detector (DUMAND) was conceived in discussions at the Denver Cosmic Ray conference in 1973 and an informal group of interested people was assembled under the leadership of F. Reines, A. Roberts, S. Miyake and J. Learned. Shortly after, a series of workshops were held whose proceedings form perhaps the most complete set of early references in the field.

The first DUMAND Workshop, held in 1975 in Washington State, considered the concept of a large undersea array of photomultiplier (PMT) tubes to detect the Čerenkov light from the charged particles produced in neutrino interactions. A survey of possible sites led quickly to the conclusion that Hawaii is the best place for such an experiment, with deep, clear water near shore.

A two-week workshop in 1976 in Honolulu initiated the involvement of the University of Hawaii. This workshop gave considerable attention to the question of the detection of neutrinos from gravitational stellar collapse. It was determined that a 10^9 ton detector mass would be needed to observe supernovae at the rate of a few per year.[3,4] Even with the ocean as the detection medium, this appeared impractical. The more recent observation of neutrinos from SN1978a by much smaller underground detectors does not invalidate this conclusion; being the brightest supernova in 400 years, this apparently was a serendipitous event.

The 1976 workshop also saw the first extensive discussion of the possible cosmic sources of very high energy neutrinos (>1 TeV), including their emission from the expanding shell of a recent supernova.[5] The possibility of acoustic detection was also proposed at that time. A workshop in 1977 was devoted to this subject,[6] but acoustic detection was eventually shown to be impractical by DUMAND workers.

The proceedings of the DUMAND 1978 workshop in La Jolla contain, to my knowledge, the first references proposing neutron star binary systems, specifically Cyg X-3, as point sources of very high energy neutrinos.[7,8] It was recognized that there should be a connection with the Tev γ-rays which had been reported

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from a handful of sources.[9] At the same time, various diffuse source possibilities were examined and found to be unpromising.[10,11]

THE DUMAND FEASIBILITY STUDY

The great international interest in the DUMAND concept reached a peak in 1979 at a series of conferences in Japan and the USSR. This encouraged the University of Hawaii and the Department of Energy to support a Feasibility Study, begun in 1980. A symposium and two workshops were held that year which considered the scientific and technological problems in great detail. The results were published in four volumes of papers.[12,13]

As part of the Feasibility Study, a series of ocean-going experiments was initiated to test the detection concepts and measure the relevant oceanographic parameters of potential DUMAND sites. This was greatly aided by the strong oceanographic capability of the University of Hawaii Institute of Geophysics. A preliminary survey conducted in 1978 had acoustically mapped two prospective sites in Hawaiian waters, obtained bottom core samples, and measured the deep ocean currents.[14] Both sites were found to be adequate, with the one off the west coast of the island of Hawaii preferred. Water clarity measurements carried out in 1980 showed that the water at this site is exceptionally clear in the blue water wavelength region important for Čerenkov light: attenuation length = 28 m at λ = 450 nm.[15,16]

Unfortunately, we also learned the hard way what our ocean experts had tried to tell us: the ocean is a hostile place. On March 7, 1982, we lost an instrument, the *Muon String*, as its support cable broke in heavy seas. Still we persevered, and in the summer of 1983 successfully deployed an instrument to measure the bioluminescence background light level.[17] A significant depth relationship was discovered and higher light levels were observed while the instrument was being raised (Fig. 1). We interpreted this as the stimulated bioluminescence seen in the instruments's wake by the down-viewing phototubes.

This interesting result spurred us on to see how the bioluminescence would appear to PMT's sitting quietly on the bottom, as they would in any permanent array. In January 1984 the apparatus was deployed on the ocean bottom. Two independent timed explosive releases, each with supposedly better than 90%

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probability of successful operation, failed to release the object from the bottom. We had lost our second instrument in less than two years.

Fortunately, DUMAND collaborators from the Institute for Cosmic Ray Research (ICRR) in Tokyo had been developing an independent experiment for measuring light background in the ocean. In summer, 1984 this instrument was deployed in a series of wonderfully successful operations at the DUMAND site.[18] First, the earlier results on stimulated bioluminescence were confirmed with ship-tethered measurements (Fig. 2). Then the instrument was placed on the bottom, with the PMT's 100 m off the sea floor, to observe quiescent conditions. This time the recovery was completely successful. The analyzed data showed that the light level 4.5 km deep, at the DUMAND site, was about an order of magnitude lower than observed at the same depth when the instrument was tethered to the ship. In fact, the measured light level of 218^{+200}_{-60} photons cm^{-2} s^{-1} was just slightly above what had been calculated and measured for the K^{40} in seawater, viz., 150 photons cm^{-2} s^{-1} for K^{40} (Fig. 2). Further, although an occasional bright pulse was seen, the light in general did not exhibit the time or pulse-height structure of the ship-tethered data (Fig. 3). We concluded that most of the biolight observed was stimulated, in disagreement with the predictions of experts. More important, for our purposes, was the conclusion that a bottom-moored array should not be washed out by bioluminescence.

This success for DUMAND was followed by another in summer, 1985, with the remarkable recovery of the instrument which had been lost at sea some 18 months earlier. The Scripps Institute for Oceanography vessel *Melville* had been cruising the Pacific picking up lost instruments. DUMAND personnel joined them in Hawaiian waters, aiding the crew locate and recover the instrument. Thus we were able to examine equipment which had rested for 18 months at the bottom of the ocean. No evidence was found for biofouling, and those parts of the instrument which had been properly treated prior to deployment were remarkably free of corrosion. Further, the data tapes were retrieved, analyzed, and found to give results on quiescent bioluminescence which were consistent with those found with the Japanese instrument. Thus we learned that the ocean is not so overpowering that we cannot fight back.

In 1982, the DUMAND collaboration had proposed to its various funding agencies that a staged program begin with the eventual purpose of placing a

$500 \times 250 \times 250$ m^3 array of 756 PMT's in the ocean for the primary purpose of very high energy neutrino astronomy (DUMAND Collaboration, 1982). Calculations indicated that if the γ-rays observed from several sources resulted from π^o production and decay, then a comparable flux of neutrinos above 1 TeV should be present (Fig. 4).[20] This implied that an array with an area of the order of 10^5 m^2 was needed to detect sources such as Cygnus X-3. This proposal was presented to the U.S. Department of Energy (DOE) in April 1983 who approved funding of the DOE-supported U.S. Groups for the first stage, the *Short Prototype String (SPS)*. NSF agreed to fund the Vanderbilt collaborators and ICRR in Japan was able to continue its significant role.

STAGE I: THE SHORT PROTOTYPE STRING (SPS)

The SPS is a string of seven optical detector modules and ancillary equipment deployed from a ship at variable depth.[21] As the first stage of DUMAND beyond the Feasibility Study, it had several purposes: (1) develop and test the basic detector module; (2) develop and test the associated technology, especially fiber optic signal communication; (3) learn more about backgrounds and other environmental parameters; (4) demonstrate that muons can be detected and their paths reconstructed by this technique; (5) measure muon depth vs. intensity with a homogenous overburden of matter. Only the last represented any attempt at obtaining new physics results. By the time of this conference, not all of this had been accomplished. Since then, a series of ocean operations in October and November, 1987, has produced excellent data at depths of 2000, 2500, 3000, 3500 and 4000 m (to be published). Thus Stage I has been brought to a successful conclusion.

The basic DUMAND detector unit, the optical module, is composed of a Hamamatsu 16-inch PMT encased in a glass pressure sphere. Electronic and power supplies are arrayed in two layers around the stem of the tube. The PMT output is converted to an optical signal whose leading edge specifies the time of arrival of the hit. The uncertainty in this time varies from 10 ns at the one photoelectron (pe) level to 5 ns for signals above 3 pe. The width of the optical output pulse specifies the collected PMT charge. The pulse width distributions are found to be Gaussian with $<PW> = 36 + 117$ q (ns) and $\sigma_{PW} = 15.4 + 36.2q$ (typically), where PW is the pulse width in ns and q is the number of

photoelectrons. The angular response of the optical modules, including any blocking by the electronics, is is typically 0.55 + 0.45 cosα, where α is the entry angle of a light ray.

The optical signal passes through the pressure sphere via a penetrator especially designed and manufactured by DUMAND personnel. Electrical power and 300 baud communications pass through a second penetrator. In addition to the signal processing circuitry in the optical module, sensors keep tabs on the environment inside the housing and a microprocessor monitors these parameter as well as providing experimenter remote control of the module circuits.

Operating at or near the single pe level, each optical module generates data at about a 100 KHz event rate from K^{40} background alone. Bioluminescence can produce even higher rates. The optical output of each detector module is carried by a multi-mode optical fiber to a central unit, the *String Bottom Controller (SBC)*, where it is multiplexed with others for transmission to the ship along a single mono-mode optical fiber. The SBC circuitry utilizes new gate array technology in order to handle the high data rates and ns timing of the signals. The fiber carrying these signals up to the ship is encased in a 6 km long 5/16-inch steel cable which also serves to support the string, send power from the ship with seawater return, and transmit 300 baud communications to and from the ship. This cable, designed for the U.S. Navy,[22] has other applications and represents another example of the development of useful new technology in the course of meeting the challenges of DUMAND.

The string also contains two modules which provide a calibrated light pulse for testing the optical modules are measuring the light attenuation length. An *Environmental Module* keeps track of depth, string orientation, acceleration and various environmental parameters including temperature and deep ocean current flow.[23] These data are transmitted to the ship via both an optical link and a much slower 300 baud link. The Environmental Module also transmits the outputs of two hydrophones which are mounted on the string to measure the acoustic background.

In order to minimize the stimulated bioluminescence as well as cable accelerations, we deploy the SPS from a stable platform, the U.S. Navy experimental research vessel *Kaimalino* (see frontispice). The Kaimalino is a

SWATH (Small Water Area Twin Hull) vessel which is exceptionally stable and thus able to operate in very rough seas.

VERY HIGH ENERGY NEUTRINO ASTRONOMY: THE BEST BET

The observation of *SN1987a* has certainly provided a welcome shot in the arm for neutrino astronomy. However, it must be recognized that this event was probably a stroke of luck which cannot be counted on to be repeated too often. The best bet for a continuing program of neutrino astronomy remains that outlined in the original 1982 DUMAND proposal: the detection of muons from very high energy (> 1 TeV) ν_μ interactions with large area underground or undersea muon detectors.

Observations of TeV and PeV γ-rays from a number of sources, mainly binary x-ray systems, strongly suggest that hadronic processes are involved. This implies a flux of ν_μ's from pion decay comparable to that observed for γ-rays from these sources. The ν_e fluxes should be much less. The preference for ν_μ over ν_e is fortunate. The great range of the very high energy muons produced in ν_μ charged-current interactions transforms any underground or undersea muon detector into very high energy neutrino telescope, with the earth or water surrounding the detector greatly multiplying the telescope's effective volume. In Fig. 5, the muon energy spectrum which would be expected from an extraterrestrial neutrino source is shown and compared with the background from atmospheric pion decays in the cosmic rays.[24] An E_ν^{-2} neutrino differential spectrum at the source is assumed, cutting off above 10^{16} eV. We see that most of the events have muon energies above 1 TeV, a result of two constructive effects: both the neutrino cross section and muon range increase with energy. The atmospheric neutrino background, on the other hand, has a steeper spectrum and the muons induced by these neutrinos are mostly below 1 TeV. The fact that there is no advantage, in fact a disadvantage, in being sensitive to muons below 100 GeV was important in the design of the proposed full-sized DUMAND array. Since virtually all of the muons will have ranges of hundreds of meters in water, the detector modules can be placed far apart, thus maximizing detector area with the minimum number of basic detector units.

In the case of Cyg X-3, the source most studied, calculations indicate that the ν_μ flux should be about three times the observed γ-ray flux above 1 TeV,

implying that a detector area of $\geq 10^4$ m^2 is needed for a signal of ten events per year.[25] The largest existing underground detector, IMB, has an area of 400 m^2. The largest planned underground experiment, *MACRO*,[26] has a surface area of 1400 m^2. These represent about the most one can practically achieve underground in mines or tunnels. Thus the original DUMAND scheme of using a natural body of water as a Čerenkov detector remains the most viable to achieve the necessary detector size.

THE NEXT STAGE OF DUMAND

The 10^5 m^2 array envisaged in the 1982 DUMAND proposal[19] represents a major undertaking. Proposals have been made for smaller arrays to be deployed on the ocean bottom as the second stage of DUMAND. A three–string, 21 PMT, array, dubbed the *TRIAD*,[27] would have an effective area for neutrino astronomy of about 3000 m^2, larger than any planned underground detector. However, as described above, areas greater than 10^4 m^2 appear to be required for a reasonable expectation of a signal given our current state of knowledge. A larger array with ∼100 PMT modules appears necessary, if the aim is to look for neutrino sources at this signal level. The optimum configuration for such an array is not yet determined. A four–string array of 64 modules has been studied in some detail;[27] it would have an effective area of about 7500 m^2. After the results from the SPS are analyzed and fed back into the Monte Carlo, these studies will be refined and a proposal for the next stage will be made. Since even 10^4 m^2 is still somewhat marginal, a 10^5 m^2 array remains the ultimate goal of DUMAND.

One possibility for a small–scale next step is to deploy a single string, perhaps the existing SPS, on the bottom. This would be relatively inexpensive, but still require the purchase of a 40 km long undersea electro–optic cable if the deployment is to reach 4.5 km. The possibility of deploying at shallower depths has been considered, but discarded because of the large cosmic ray background. Even at 4.5 km, a full 7–fold coincidence is required to limit the fake upcoming neutrino events to below one per year, corresponding to an effective area of 200 m^2. It must also be noted that a single string provides only zenith angle information, azimuth being undetermined.

An interesting added feature of a bottom–moored string, which might help justify its deployment, is the search for heavy particle candidates for the dark

matter of the universe such as nuclearites (quark nuggets) and pyrgons (the particles associated with the compactification of higher dimensions). If these particles are of atomic dimensions and constitute the major mass of the galaxy, they can emit sufficient light to be detected undersea with a few phototubes.[28]

COMPARISON WITH OTHER UNDERWATER PROPOSALS

Ideally one would like the clearest possible water for the detector. The ocean is unfortunately contaminated with salt and all natural bodies of water contain living organisms. As I have said, measurements at the proposed DUMAND site indicate that the background light under quiescent conditions near the bottom is essentially that produced by the radioactivity of the salt. Bioluminescence dominates only when the critters are disturbed.

The Soviets, who have carried on their own DUMAND project in parallel with the one reported here, report background light studies in the ocean consistent with those reported above.[29] They have also successfully deployed a string of PMT's at depths 850–1350 m in the fresh water of Lake Baikal, which has already set useful limits on magnetic monopoles.[30] Ultimately they plan to build a 4×10^5 m^2 area array and the project appears to be well-supported. In the U.S., a 62,500 m^2 water Cerenkov detector in a shallow lake or pit has been proposed.[31]

The Baikal experiment also reports that the attenuation length of the water in the lake is 20 m at 500 nm wavelength. Comparing this with 28 m for the water off Hawaii, we note that deep ocean sea water is clearer than fresh water in a natural lake, probably because of a higher density of biological matter in the lake.

Experiments in lakes or pits do not have the open hostility of the ocean to contend with, but pay a price for this convenience. Deployed in shallow water, they must cope with the enormous cosmic ray muon background. Background reduction is accomplished by operating the phototubes at a high level of coincidence. In order to keep the coincidence time window sufficiently short, the tubes in coincidence must be close together. This clashes with the need to have tubes far apart to maximize the area. Thus the tradeoff is between going deep into the ocean, with the problems of ocean deployment, or building a shallow array in fresh water with perhaps an order of magnitude as many PMT's operated at a

high level of coincidence. At this time there is no obvious reason to decide which is the better option.

CONCLUSIONS

Although DUMAND has yet to see a neutrino, the DUMAND project has contributed significantly to the advance toward extrasolar neutrino astronomy. Much of the early work in neutrino source astrophysics and detector concepts was done in relation to DUMAND, with the proceedings of DUMAND workshops providing a major resource for the field. The notion of a deep ocean Čerenkov detector has been pursued by the international DUMAND collaboration, centered at the University of Hawaii. Our group of particle and cosmic ray physicists has gained considerable experience at operating in the ocean. We have recently succeeded in measuring muons in the ocean to a depth of 4000 m in what independent observers have called "the most sophisticated experiment ever done in the ocean." We have also made important measurements of ocean parameters and light backgrounds which will be invaluable to the development of any deep ocean installation and contributed to the development of a number of technologies which can be applied in the ocean and elsewhere.

The best bet for a continuing program of extraterrestrial neutrino astronomy remains the original DUMAND concept of detecting and reconstructing muons produced by the interaction of ν_μ's in the earth or sea. Unfortunately, ν_μ fluxes in the energy range where detection is optimum, above 1 TeV, are not expected to greatly exceed observed γ-ray fluxes, according to our best current estimates. In the case of Cyg X-3, an area $\sim 10^4$ m^2 is required, probably impractical anywhere on earth but underwater.

Experiments in comparatively shallow lakes and pits have been proposed which will have sufficient area, but require large numbers of phototubes operated at high coincidence levels to reduce the high background from downward cosmic ray muons. DUMAND would operate at a great depth in the ocean where the cosmic ray background is far lower, but must contend with a more hostile operational environment.

The DUMAND project has just completed its first stage, the Short Prototype String, which looked only at cosmic ray muons at great depths in the ocean. The

DUMAND approach to neutrino astronomy remains a viable alternative. If neutrino astronomy is worth doing, something like DUMAND will likely eventually be built.

ACKNOWLEDGEMENTS

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PHOTONS cm⁻² · S⁻¹

10^6

10^5

10^4

10^3

△ ASCENT
⊙ PAUSE
▽ DESCENT

1.6×10^3

10^3

1.6×10^2

10^2

$I = 2.008 \times 10^5 \exp\left[-X/960\right]$

16

10

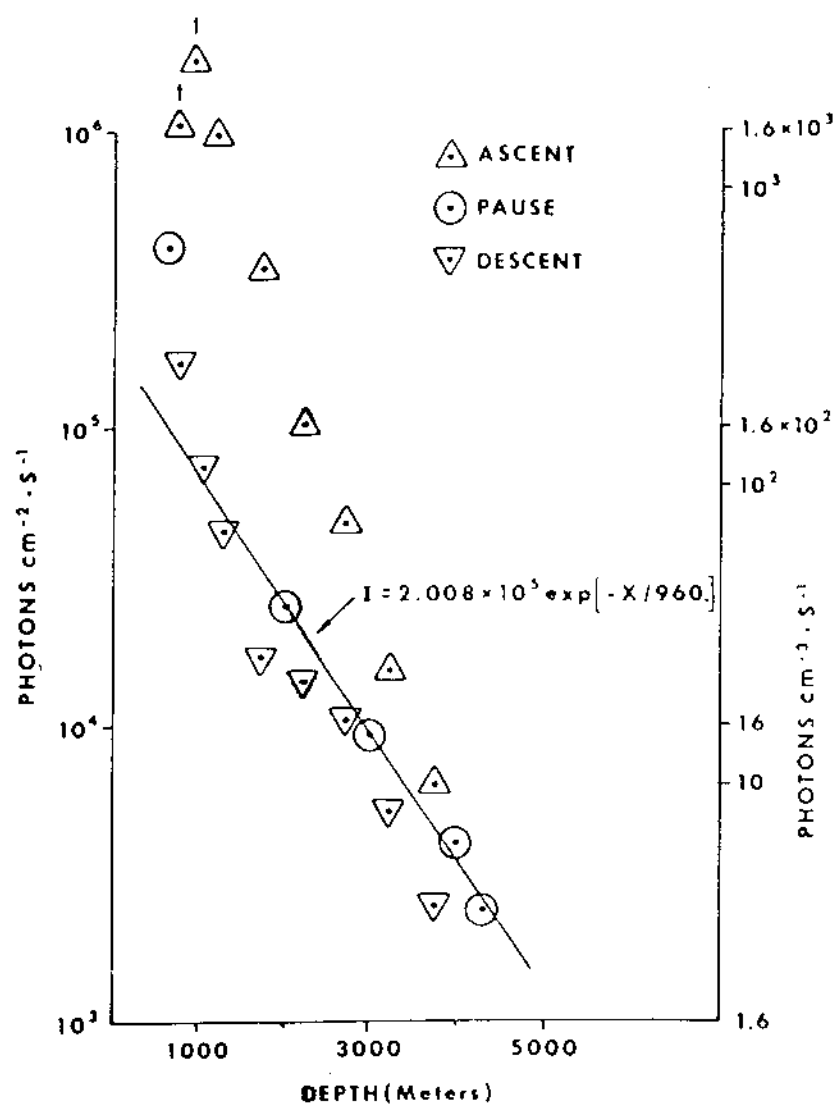PHOTONS cm⁻² · S⁻¹

1.6

1000   3000   5000

DEPTH(Meters)

Fig. 1. Biomuminescent light intensity as a function of depth measured in the 1983 DUMAND ship-tethered experiment. The photomultiplier tubes look down and the greater intensity observed during ascent is interpreted as the stimulation effect of the instrument's wake. From Reference 17.
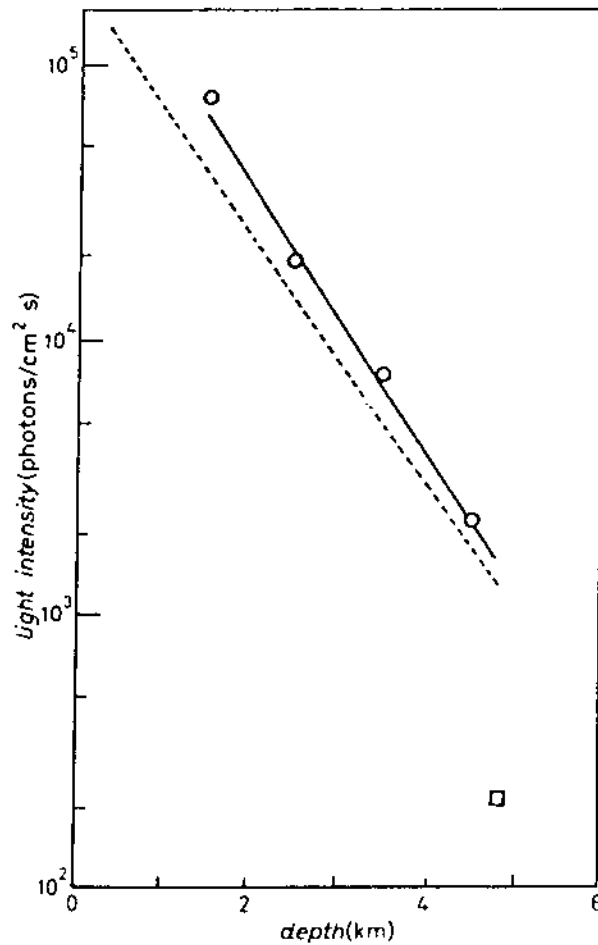
Fig. 2. Biomuminescent light intensity as a function of depth measured in the 1984 experiment. The circles are ship-tethered data. The square is the data point taken under quiescent conditions, with the instrument on the bottom. The level expected from K^{40} is 150 photons cm^{-2} s^{-1}. The dashed line is the previous ship-tethered result of Bradner *et al.*[17] From Reference 18.
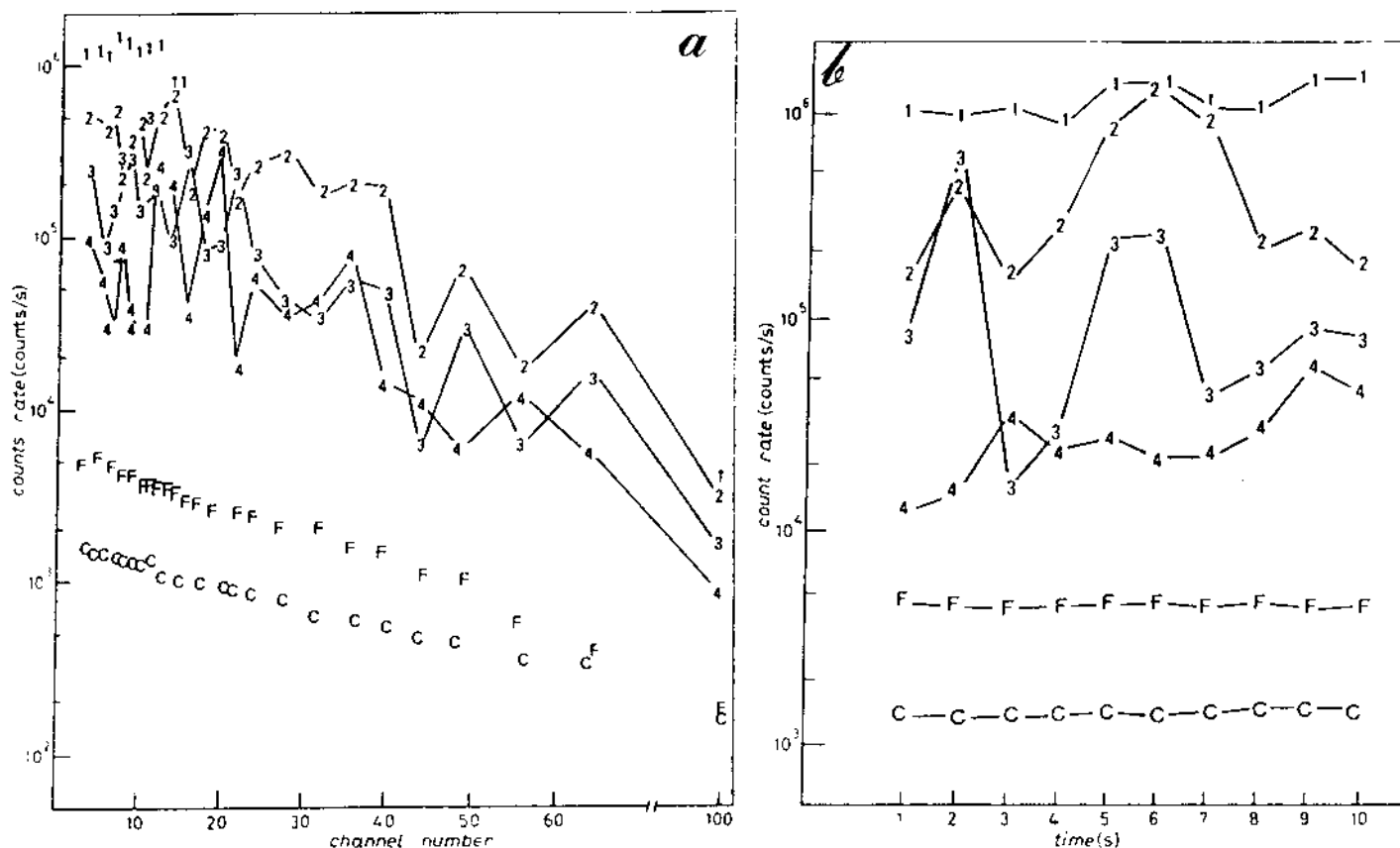
Fig. 3 (a) Pulse–height spectrum of background light from Reference 18. The data labeled 1–4 are for the depths 1500, 2500, 3500, and 4500 m respectively. The data labelled F are for the instrument moored near the bottom. The data labelled C are for dark noise measured at 3°C in the laboratory: (b) Time variation in the count rate for these data.
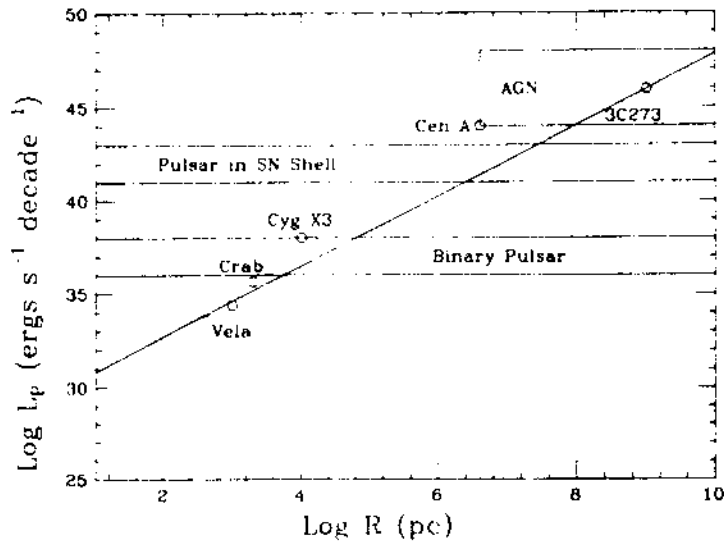
Fig. 4. The range of proton energy luminosities for types of possible very high energy neutrino sources and some specific examples. The diagonal line shows the detectability level for a full-scale DUMAND array. From Reference 20.
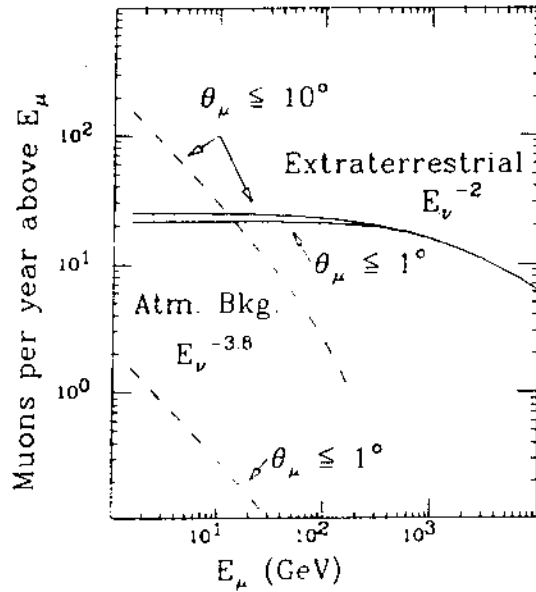

Fig. 5 The solid muon spectrum (solid) which would be measured by an underground or undersea muon detector from a source, such as a binary pulsar, which has an E_{ν}^{-2} differential neutrino spectrum. The flux is normalized to give 20 events per year. Two cuts on the radius θ_{μ} of the muon circle on the celestial sphere are shown. The dashed curve shows the background from ν_{μ}'s produced in the atmosphere which would be observed in a detector of area 1000 m^2, in each of the two muon circles. From Reference 24.