DUMAND-Deep Underwater Muon and Neutrino Detection

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Neutrino Astronomy and Astrophysics with the Dumand Stage II Octagon Detector

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ABSTRACT

We present the scientific goals and capabilities of the DUMAND Stage II detector system. The proposal for the construction of Stage II had been recommended by the High Energy Physics Advisory Panel (HEPAP) to the U.S. Department of Energy (DOE) for support in June 1989. The funding profile had been released by DOE at the end of April 1990. Details of the array are also outlined.

1. INTRODUCTION.

DUMAND is a project to build a deep underwater laboratory for the study of:

1. **high energy neutrino astrophysics**, principally the detection of galactic and extragalactic point sources of TeV neutrinos;

2. **particle physics**, via indirect observations of UHE hadronic interactions in astrophysical objects as well as more direct observations of terrestrial interactions;

3. **cosmic ray physics**, relating to muon, primary energy spectrum and composition studies;

4. **geophysics and ocean science** issues are confronted incidentally.

DUMAND-II consists of an octagonal array of 216 high sensitivity photomultiplier tubes, capable of detecting position and direction of single relativistic charged particles with a uniquely large sensitive volume and an angular resolution of about 1^o. The array will be shielded by 4.8 km of water to minimize the incidence of common cosmic ray particles in the detector. The project will be sited in an ocean valley approximately 25 km west of Keahole Point on the Island of Hawaii.

1.1 Physics Motivations

Point sources of high energy neutrinos The formation of rotating neutron stars through the gravitational collapse of ordinary stellar objects appears to provide the extraordinary conditions needed to accelerate hadrons to energies far beyond the foreseen capabilities of any terrestrial machine. These neutron stars, with rotational energy in excess of 10^{50} ergs and surface magnetic fields of 10^8 tesla, are the central engines responsible for the prodigious energy outputs of both radio pulsars and compact galactic x-ray sources. Evidence is mounting that both these classes of neutron star systems are sources of VHE and UHE gamma rays, and therefore of associated high energy hadron and neutrino fluxes.

We expect detectable signals in the second stage of DUMAND from a number of point sources both inside and outside the galaxy. DUMAND also has a chance of seeing the diffuse background of neutrinos produced by cosmic rays passing through the denser portions of our galaxy. We are, of course, optimistic that DUMAND will follow in the tradition of all of the other branches of astronomy, and discover unanticipated objects and phenomena once a detector of completely new capabilities is opened to the universe. The long range goal of the DUMAND collaboration is to begin the regular observation of the universe in this new light. a task that only particle physicists are qualified to carry out, and probably only from the deep ocean.

High Energy Neutrino Physics In addition to opening new territory in astrophysics and astronomy, DUMAND will complement accelerator-based high energy physics research. There are two classes of studies: those that search for new phenomena, and those that measure characteristics within the prevailing model. DUMAND offers us some of both. The currently existing or planned accelerator facilities offer no neutrino beam above about 600 GeV, while DUMAND explores energies above 1 TeV.

The fact that neutrinos and muons are both produced in the same interaction implies a relationship between the downward atmospheric muon and neutrino intensities. Hence improved measurements of muon flux at this depth enable us to calibrate the neutrino "beam" and to push the study of high energy neutrino interactions into an energy region which will not be available at any planned accelerator. The rising neutrino cross section and the greater effective volume of DUMAND offers the best available opportunity to continue the very fruitful study of neutrino interactions energies above 1 TeV where important W-boson propogator and QCD effects are expected.

The observation of neutrinos from astrophysical sources offers the opportunity to study, albeit indirectly, characteristics of interactions in esoteric circumstances far beyond our ability to reproduce in the laboratory, and which may thus reveal new facets of particle physics: 10^{12} Gauss fields, gravitational field strengths where general relativistic effects are not negligible, matter densities greater than in the core of the sun, photon field densities such that photon–photon scattering must be accounted for, macroscopic matter velocities at a significant fraction of the velocity of light (as on the magnetopause of an accreting neutron star), neutron star matter that may contain a stable mixture of up, down and strange quarks, remarkable electromagnetic phenomena such as curvature radiation and radiation from Landau transitions, power levels that are a million times that of our sun, and particle acceleration to energies of at least 10^{17} eV. How these extreme conditions manifest themselves in terms of neutrino observations we do not yet know in detail. The experimental handles are source identification, the neutrino spectrum, nature of the beam (particle content), and temporal variations, particularly as correlated with other observations. The combination of sweeping beams and magnetic fields may even offer momentum analyzed beam on target (e.g. as suggested by the VHE gamma observations from Her X-1 during eclipse).

Neutrino Oscillations DUMAND will also have the ability to study more conventional particle physics questions. These studies will rely primarily on the dominant component of DUMAND's neutrino "beam", muon neutrinos of atmospheric origin. Measurement of the neutrino induced muon angular distribution (with particular sensitivity to the region near the horizon), will give a neutrino mass sensitivity in the range $0.01 \leq \delta m^2 \leq 100eV^2$ for mixing angles $\sin^2(2\theta) \geq 0.1$. Five years of data from DUMAND will result in a factor of five improvement in statistical precision over the sum of all the present and planned underground experiments. At this moment it seems that only non-accelerator experiments have the ability to observe neutrino oscillations.

Dark Matter Searches No more important issue for cosmology and particle astrophysics exists than the nature of the missing "dark matter", and DUMAND should be able to make unique contributions to that search. It must be emphasized that DUMAND will be unmatched by any other detector in the world for sheer area and volume. The catalysis of baryon decays by magnetic monopoles presents an outstanding current example. This process would give an easily recognizable signature in DUMAND. The recent history of high energy theory indicates that predictions of this sort come along every few years, and some of the objects of processes predicted may be observable in DUMAND. In searching for rare phenomena, DUMAND will be capable of setting limits several orders of magnitude better than any other detector.

Cosmic Ray Physics DUMAND can provide information on the origins and acceleration mechanisms of the primary cosmic rays. It provides a new data channel that complements existing cosmic ray detectors at the upper end of the energy spectrum. such as extensive air shower arrays and the "Fly's Eye." The measurement of the muon energy distribution via the angular distribution of down-going muons, and observation of the spectrum of electromagnetic bursts caused by down-going muons will enable us to study the spectrum up through the UHE range.

Ocean Physics DUMAND will also present unprecedented opportunities for long term deep ocean observations. Without any special additions to the particle physics-oriented design the array will collect a vast quantity of environmental information simply while monitoring the conditions at the array. Of interest are the ocean currents and other physical parameters, and bioluminescence (seasonal fluctuations, diurnal variation, spatial correlations, etc.). (We expect of the order of one percent deadtime due to bioluminescent activity, based upon our previous background studies.) We will also have hydrophones intermixed with optical modules. We need these to keep track of the location (to about 1 m) of the strings (we expect a motion at the top of the strings of less than 10 m in the largest current).

Acoustical Particle Detection Secondarily, we will carry out a search for UHE neutrino induced acoustic pulses. This acoustic array may have interest to others who study ocean acoustic tomography, for example.

2. History and Deployment Plans

Stage I of the DUMAND (Deep Underwater Muon and Neutrino Detector) project, which included development, construction, deployment and operation of a "Short Prototype String (SPS)" detector system in the deep ocean, was successfully completed in late 1987. The system which consisted of seven optical sensor modules (Matsuno et al., 1989), two calibration modules, environmental monitoring devices, sonar telemetry systems and an elaborate data acquisition, processing and transmission system, was capable of reconstructing cosmic ray muon trajectories in the deep ocean.

Preliminary results of this experiment, which included the measurements of the depth - intensity relation of high energy cosmic ray muons and their zenith angle distribution at various depths between 2000 m and 4200 m as well as background measurements, had been presented at the NEUTRINO 88 meeting in Boston (Stenger, 1988). A more detailed report will appear elsewhere (Babson et al., 1990).

This experiment demonstrated the practicability of the DUMAND principle and detector module capabilities. As a next step towards a truly giant deep ocean detector, the DUMAND collaboration has designed an intermediate size detector, DUMAND Stage II.

In August 1988 the entire collaboration submitted a joint proposal for the construction of DUMAND Stage II to the U.S. Department of Energy (DOE), the anticipated lead agency for supporting the project. After unanimous recommendation of the proposal by the High Energy Physics Advisory Panel (HEPAP) to DOE in June 1989, the non-U.S. groups of the collaboration submitted their respective portions of the proposal to their national funding agencies. At the end of April 1990 DOE announced the funding profile and gave the go-ahead for DUMAND Stage II.

3. DUMAND STAGE II: The Octagon Array.

Figure 1 shows the configuration of the planned ocean bottom- -moored array. It will consist of a total of 216 optical modules of 32 of the type developed for the SPS, mounted on nine vertical strings of 24 modules each. The strings are located at the corners of an equilateral octagon. with the ninth string at its center. The array will have a height of 230 m and a diameter of 105 m. Horizontal and vertical spacings between the modules are 40 m and 10 m, respectively. The lowest module will be approximately 100 m above the ocean floor.

Size, and configuration of the array have been chosen after extensive studies as the simplest and least expensive technique which can do unique and important **High-energy neutrino physics and astrophysics**. In addition, it will have a significant capability in **High-energy cosmic ray physics and Ocean science** Moreover, the chosen detector size should yield a reasonable event rate and adequate sensitivity to **detect extraterrestrial high-energy neutrino sources at their expected flux levels.**

The planned site for the array is approximately 30 km west of Keahole Point on the Island of Hawaii ("Big Island"). at a depth of 4.5 km. This is the location where we have carried out our measurements with the SPS. The site has been extensively explored over the last decade, and has been found to be adequate to our needs.

Early concerns about biofouling and bioluminescence have been investigated and were found not to present a serious problem.

4. ARRAY CAPABILITIES.

The array has been optimized for the detection of HIGH-ENERGY MUONS from neutrino interactions. Calculations indicate that this choice is the best compromise for detecting extraterrestrial neutrino sources. Moreover, it has the ability to detect contained neutrino induced cascades. The detector spacings ensure that muons with energy greater than 50 GeV which pass through from outside, will be detected with high efficiency and reconstructed in direction with a median accuracy of about 1^o. The scattering angle between the incident neutrino and the resulting muon will be within this error for neutrino energies above about 1 TeV.

Muons generated by cosmic rays will be incident at all angles. There will be a higher rate in the 80^o zenith cone which come from decays of secondaries. Beyond 80^o, the muons will be dominated by muons produced from neutrinos which were produced by cosmic ray secondaries. These latter are called *atmospheric neutrinos* and the former are called *cosmic ray muons. Atmospheric neutrinos* yield a very low rate of muons so that we have an excellent window for observing extraterrestrial neutrino sources for zenith angles beyond 80^o.The solid angle for this window is 2.35 π steradians. This is illustrated in figure 2 which shows the counting rates per degree and year for muons from cosmic rays as a function of zenith angle.

The rate of cosmic ray neutrino induced muon events will be about 3500 per year. This gives a background of about one *atmospheric neutrino* per $(2.8^o)^2$ per year. Thus, with the calculated resolution of 1 degree for muon direction reconstruction, we will be largely signal limited, rather than background limited, in the search for extraterrestrial point sources.

The array will contain hydrophones which will explore the possibility of acoustic detection for future explorations at or above ultrahigh energies, and it has the ability to be expanded to any size in the future. The major characteristics of the array are summarized in table 1.

TABLE 1: Summary of Major Array Characteristics.

Array dimensions	105 m diameter, 230 m high
String spacing	40 m side, 50 m to center
Number of strings in array	8 on contour, 1 in center
Sensor spacing along string	10 m
Number of optical sensors/string	24
Total number of optical sensors	$9 \cdot 24 = 216$
Height of first sensor	100 m above sea floor
Depth of sea floor	4.8 km
Sensor pressure envelope	17" (43.2 cm) O.D., glass
Optical sensor	16" photomultiplier
Volume of array, contained	$1.8 \cdot 10^6\ m^3$
Target area for through-going muons	26,000 m^2 horizontal 17,000 m^2 vertical upward 12,000 m^2 vert. downward
Area-solid angle product for neutrino induced muons	148,000 m^2 sr
Effective target volume for 2 TeV muons	$1.0 \cdot 10^8\ m^3$
Effective target volume for 1 TeV cascades	$7.0 \cdot 10^5\ m^3$
Muon energy threshold	20 to 50 GeV

Track reconstruction accuracy	1.0^omedian
Cascade detection threshold	approximately 1 TeV
Muon rate, down-going	6 per minute
Atmospheric neutrino detection rate for through-going muons	3500 per year
Atmospheric neutrino detection rate for contained events > 1 TeV	50 per year
Point source sensitivity	4 *to* 7 $\cdot$ 10^{-10} $cm^{-1}sr^{-1}$ per year above 1 TeV
Contained event sensitivity	$1 \cdot 10^{-8} cm^{-2} s^{-1}$ per year above 1 TeV

4.1 Astrophysical Sources of High-Energy Neutrinos:

We expect detectable signals in the second stage of DUMAND from a number of point sources both inside and outside the galaxy. DUMAND also has a chance of seeing the diffuse neutrinos produced by cosmic rays passing through the denser portions of our galaxy. Figure 3 shows a number of likely extraterrestrial neutrino sources and their expected intensities in muon detections. The estimates are based on gamma ray intensities. In figure 3 we have characterized the sources as having been identified at least two times and some which need verification by other sightings. Some of the sources are already constrained by existing underground detectors.

The presence of a VHE gamma ray installation on Haleakala, which has a companion extensive air shower array, and the world's foremost site for ground-based astronomy on nearby Mauna Kea, will permit simultaneous multispectral studies of the same object, not possible at present anywhere in the world. These other instruments can provide the "beam on" signal; or, operating continuously, DUMAND can provide the "beam on" signal for them.

Moreover, there are also significant daily fractions of temporal overlap between DUMAND operating in neutrino mode and gamma ray detectors in other parts of the world, that allow simultaneous observation of the same astrophysical objects in the two kinds of radiation. The same is true for a number of underground installations, such as IMB, Baksan, Soudan and KGF, that can look for downward going cosmic ray muons, that may possibly be produced by high energy gamma rays in the atmosphere, while DUMAND is looking for upward going muons induced by neutrinos from the same source.

4.2 Cosmic Ray Studies:

Although optimized for up-coming muons from neutrinos, DUMAND will still have an effective area of 12,000 m^2 for downward-going muons, or a yield of $3.3 \cdot 10^6$ events per year for cosmic ray studies; of these about 2% will be simultaneous multiple muons. The up-down asymmetry of the array is due to the lacking isotropy of the photomultipliers, which are facing downward and have a reduced sensitivity in the backward hemisphere.

The determination of the muon energy spectrum from the angular distribution of down-going muons, and by measuring the spectrum of the electromagnetic bursts caused by the muons, will enable us to study the primary cosmic ray spectrum up through the UHE range.

Since DUMAND will be able to determine the energy flow in tight muon bundles of a few meters in diameter, and resolve multiple muons with spacings of about ten meters or more, it will be able to carry out primary composition studies based on high-energy multiple muons with high statistics in the much disputed primary energy region between 100 and 1000 TeV.

4.3 Elementary Particle Physics:

In addition to opening new territory in astrophysics and astronomy, DUMAND will complement accelerator-based high-energy physics research, since there are no existing or planned facilities that offer a neutrino beam above about 600 GeV.

The fact that neutrinos and muons are both produced in the same interaction implies a relationship between the downward atmospheric muon and neutrino intensities. Hence improved measurements of the muon flux at DUMAND depth enable us to **calibrate the neutrino "beam".**

The rising neutrino cross section and the large effective volume of DUMAND offer the best available opportunity to study **neutrino interactions** at energies above 1 TeV, where important W-boson propagator and QCD effects are expected, using the *atmospheric neutrinos.*

DUMAND will be capable of setting limits several orders of magnitude better than any previous detector in search for **exotic particles, rare phenomena, such as Wimps, dark matter, baryon decay by magnetic monopoles,etc.** In addition it can investigate **neutrino oscillations** and make unique contributions in the range $0.01 \leq \delta m^2 \leq 100\ eV^2$, for mixing angles $sin^2(\theta) \geq 0.1$.

5. CONCLUDING REMARKS.

The schedule for the DUMAND octagonal array foresees the beginning of data taking with the first three strings by late 1992 and regular observation of the universe in "neutrino light" with the complete array in 1993.

6. ACKNOWLEDGMENTS:

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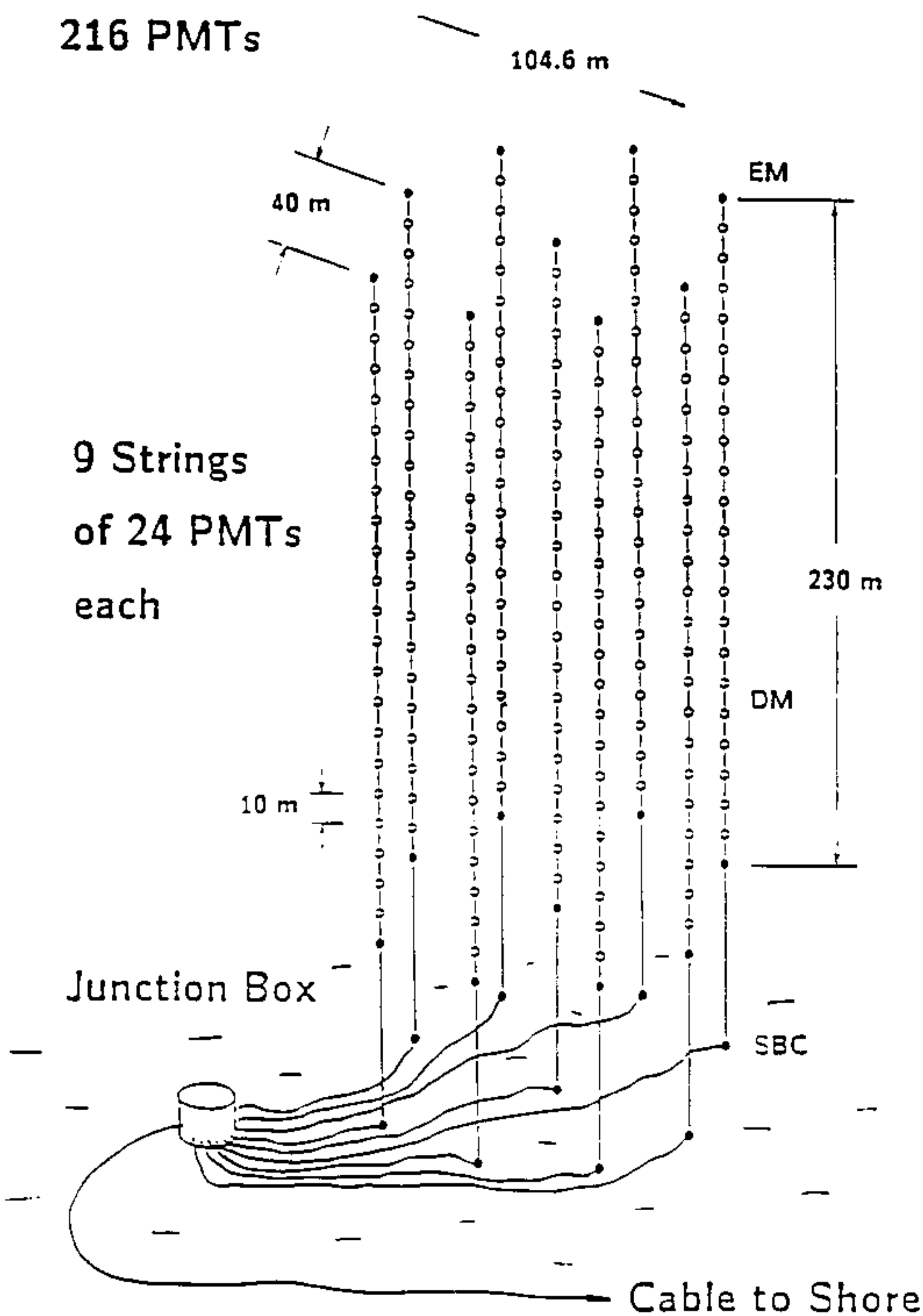
2) J. Babson. B. Barish, R. Becker-Szendy, H. Bradner. R. Cady, J. Clem. S. Dye, J. Gaidos, P. Goram, P.K.F. Grieder, T. Kitamura, W. Kropp, J.G. Learned. S. Matsuno, R. March, K. Mitsui, D. O'Connor, Y. Ohashi, A. Okada, V.Z. Peterson. L. Price, F. Reines, A. Roberts, C. Roos, H. Sobel, V.J. Stenger, M. Webster and C. Wilson; University of Hawaii preprint, HDC-1-89 (1989).

FIGURE CAPTIONS

1. The Dumand II Octagon Array
2. Calculated distribution of through-going muons from cosmic rays in the DUMAND Stage II array from *cosmic ray muon and atmospheric neutrino* events, as a function of the muon zenith angle θ_μ.
3. Extraterrestrial source detection capabilities of the DUMAND Octagon array. Shown is the number of muon detections from a particular source per year versus source distance. The closed points are from sources which have had two or more sightings. The open points have been sighted by only one observer.


216 PMTs
104.6 m
40 m
EM
9 Strings
of 24 PMTs
each
230 m
DM
10 m
Junction Box
SBC
Cable to Shore

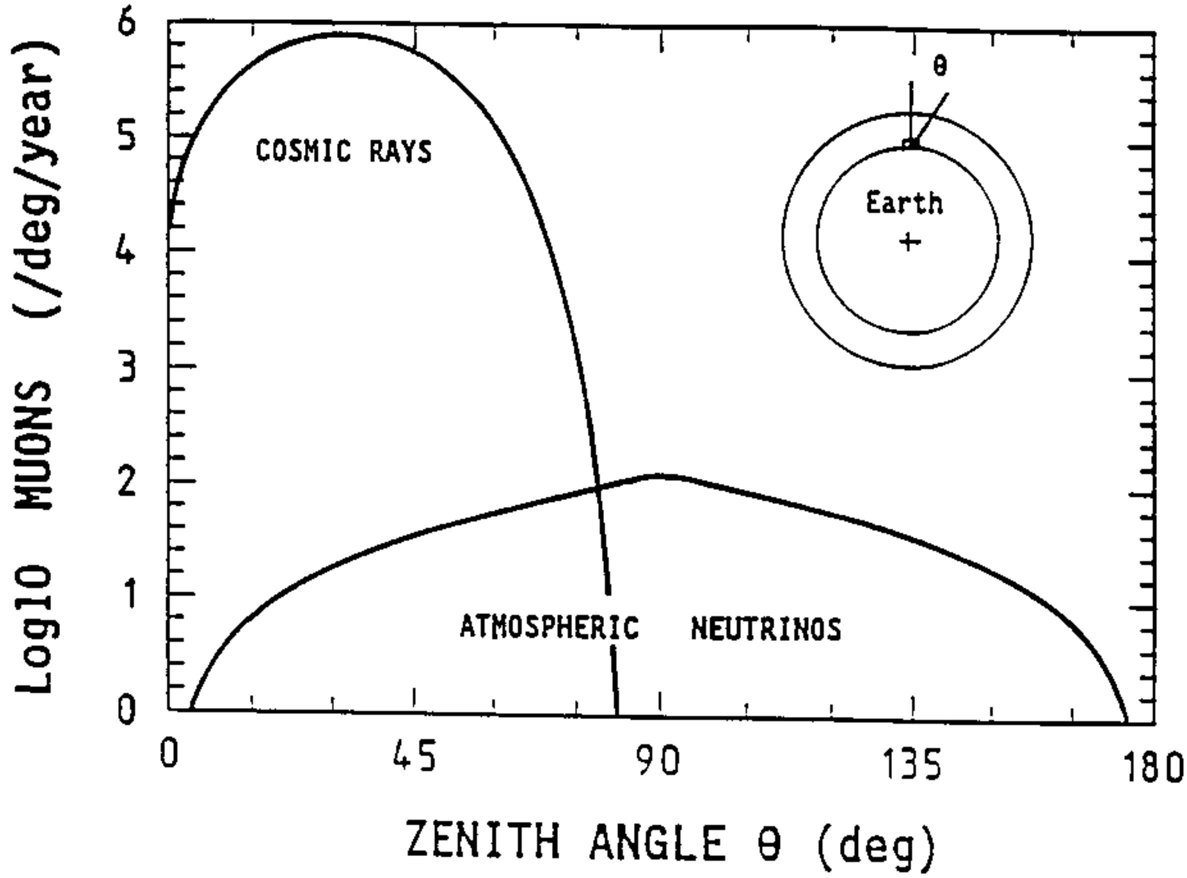


Fig. 2

Calculated distribution of through-going muons in the DUMAND Octagon Array from cosmic rays and atmospheric neutrino events as a function of the muon zenith angle θ.

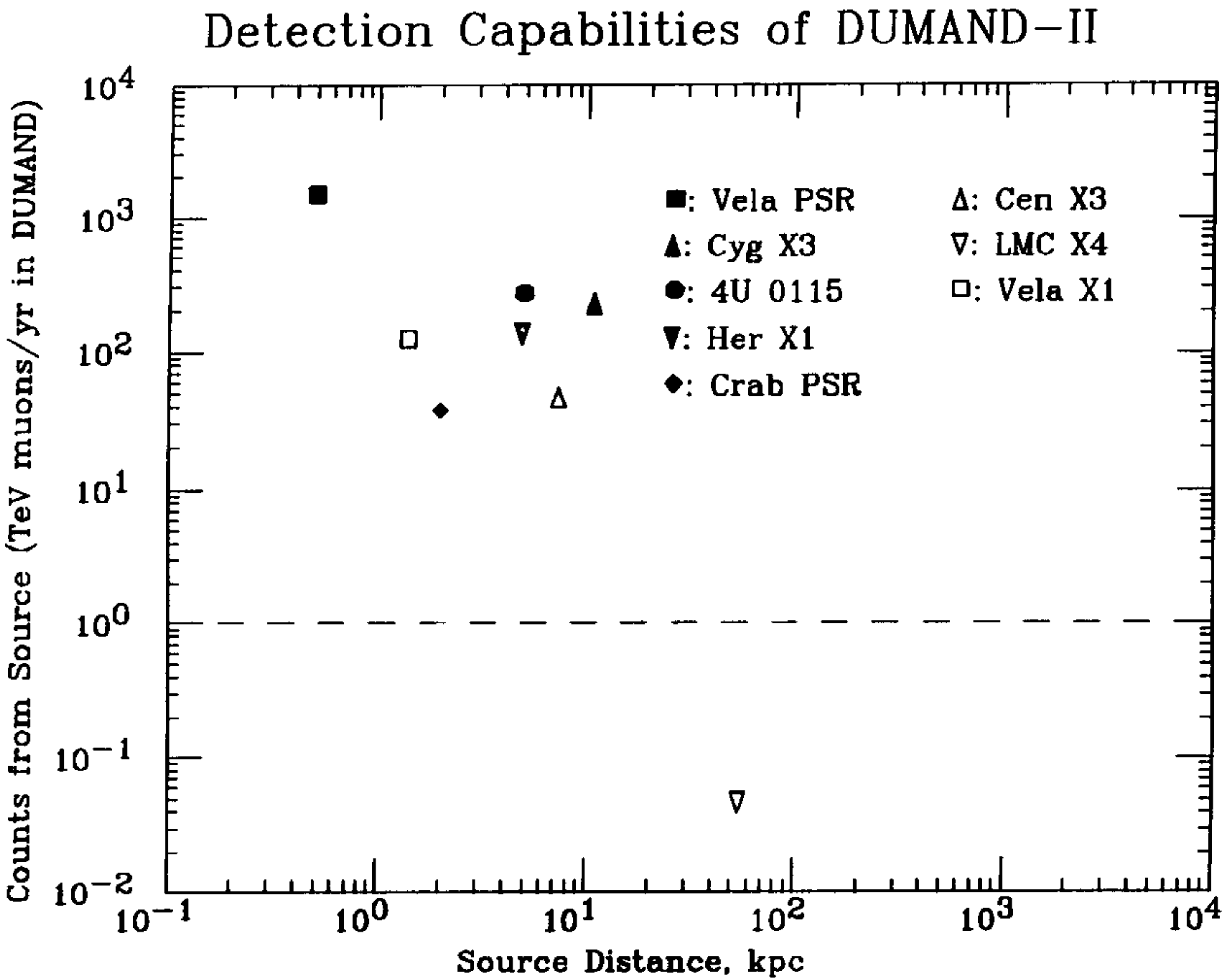

Detection Capabilities of DUMAND−II
■: Vela PSR
▲: Cyg X3
●: 4U 0115
▼: Her X1
◆: Crab PSR
Δ: Cen X3
∇: LMC X4
□: Vela X1
Counts from Source (TeV muons/yr in DUMAND)
Source Distance, kpc
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

Fig. 3