HDC-82-10
SEPTEMBER 1982

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V.J. STENGER

INTERNATIONAL WORKSHOP ON VERY HIGH
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ABSTRACT

The intimate connection between gamma ray and neutrino astrophysics at very high (TeV) energies is discussed. It is shown that the proposed undersea Cerenkov detector DUMAND has a sensitivity to neutrinos which is comparable to the gamma ray sensitivity of atmospheric Cerenkov detectors and orders of magnitude greater than underground experiments. There are good reasons to expect that DUMAND will detect sources of neutrinos on both the galactic and extragalactic scales. Measurements of gamma ray and neutrino flux spectra from a given source are complementary and enable the determination of the matter density and thickness of matter surrounding the source.

INTRODUCTION

The study of very high energy gamma rays using the atmospheric Cerenkov technique has common and complementary interests with very high energy neutrino astrophysics. High energy gamma rays can result from electromagnetic or hadronic sources. In the latter case they are almost exclusively the decay products of π^0 mesons produced by the interaction of cosmic ray protons or nuclei and matter. Since charged pions are also produced in these same reactions, and neutrinos are a major product of their decay, there is an intimate connection between gamma rays and neutrinos. If observed high energy gamma rays result from hadronic processes, then the measured fluxes are approximately a lower limit on what will be found for neutrinos. If no neutrinos are found at that level, this will imply an electromagnetic origin of the high energy gamma rays which have been reported. If neutrinos are found without accompanying gamma rays, this will mean that the source is hadronic but so deep in matter that the photons have been absorbed.

Any detector sufficiently shielded from cosmic rays can be used as some kind of neutrino telescope. A number of experiments have been done, or are presently being done, in mines.[1-2] None has yet reported any neutrino signal beyond what is expected from the neutrinos produced by the primary cosmic rays hitting the atmosphere.

The large underground detectors which are just going into operation to search for proton decay will also be neutrino telescopes, with greater sensitivity than previous experiments. Atmospheric neutrino events are the major backgrounds in these experiments, but the experimenters will certainly be on the lookout for extraterrestrial events as evidenced by any directionality on the celestial sphere. However, despite being better than anything previously, these underground experiments are only sensitive to fluxes at least three orders of magnitude higher than what has been measured for very high energy gamma ray sources, which is typically 10^{-10} cm^{-2} s^{-1} above 1 TeV. The only experiment which is being planned which will be sensitive to neutrinos at this level is the proposed undersea laboratory, DUMAND.

THE DETECTION OF VERY HIGH ENERGY NEUTRINOS WITH DUMAND

DUMAND is a deep undersea laboratory being proposed for the study of high energy neutrino astrophysics, cosmic ray physics and neutrino physics. It is proposed to deploy an array of 756 photmultiplier tubes at a depth of 4.7 km, 25 km off the west coast of the island of Hawaii and connected to there by ocean bottom cables. The array is composed of 36 vertical strings arranged in a grid and spaced 50 m apart. Each string contains 21 phototubes plus other sensors spaced 25 m apart. The shore cables carry power and control signals to the array, and data from the array. Signals are transmitted along the shore cable and vertical strings by fiber optics.

The detector concept is illustrated in Figs. 1 and 2. The array is shown in Fig. 3. The phototubes detect the Cerenkov light emitted by the passage of high energy muons through the array and electromagnetic and hadronic showers in the array. These muons can be cosmic rays which penetrate to the array (at least 3 TeV at sea level is required). For zenith angles above about 70°, however, they will be almost exclusively the products of the charged current interaction $\nu_\mu N \rightarrow \mu X$, where N is a target nucleon in the water in and around the array and X represents any hadrons produced. The effective detector mass for these interactions is an increasing function of energy, reaching 460 Megatons for $E_\mu = 2$ TeV. The direction and energy of the muon are reconstructed from the position, time and pulse height of the signals from the photomultipler tubes in the array.

An international collaboration of groups from the Universities of Hawaii, California, Wisconsin, Purdue, Caltech, Vanderbilt, Kiel and Bern, and the Institute for Cosmic Ray Research, Tokyo, has been formed to build and operate the array. An omnibus proposal for a five year program to build and begin operating the experiment is almost ready for submission. The estimated cost is about $10 million.

DUMAND will be the first detector large enough to be able to detect high energy (>100 GeV) neutrinos from extraterrestrial sources if they exist at the level expected. The minimum detectable flux[3] above 1 TeV is $\cong 2\times10^{-10}$ cm^{-2} s^{-1}. DUMAND is a close sister to the experiments being discussed in this workshop. The same technique, Cerenkov detection is used, in water rather than air, and the flux sensitivity is comparable, at least to the air Cerenkov systems used so far. But, as already mentioned, the data obtained complements rather than competes with those on gamma rays. One of the aims of this paper is to show how data on TeV gamma rays and neutrinos from a point source can be used together to obtain information about the matter in the vicinity of that source.

Extraterrestrial Neutrino Sensitivity of the DUMAND Array

The DUMAND array will register, with high efficiency, muons produced by neutrino interactions inside the array volume and muons passing through from outside. The latter may be from neutrino interactions in the surrounding water or cosmic ray muons which penetrate to the array. At zenith angles above about 70^o we can be sure that they are neutrino-induced. Cutting out those below $70-75^o$ will cause a loss of 25-30% of the solid angle, i.e., give about a 3π field of view. However, since the latitude of the site is about 19.6^oN, the zenith describes daily circle about the north pole of 70^o radius and, unlike any detectors at higher latitudes, there will be no region of the sky which is permanently obscured.

The sensitivity of DUMAND to extraterrestrial neutrino sources can be expressed in terms of the minimum detectable flux (MDF)[3]. This will depend on the background of neutrinos produced in the atmosphere.

The DUMAND array will detect thousands of atmospheric neutrino interactions over all angles per year, but only those within a specified angular "window" constitute a background for astronomical studies. Monte Carlo calculations[4] show that the angular resolution of a muon track can be as good as 15 mr. At this level the error in the measurement of the neutrino direction $\delta\theta_\nu$ is comparable to the scattering angle θ_μ of the interaction, which is typically less than $\theta_\mu = 25/\sqrt{E_\nu}$ mr, with E_ν in TeV[5]. The result is that the atmospheric background to a point source is less than 1 event per year above 1 TeV. For diffuse sources the window is set by the size of the source, which could be the full 4π, in which case the background is considerably larger.

The procedure we have followed is to calculate the background event rate N from atmospheric ν and $\bar{\nu}$ in the specified angular window. The extraterrestrial event rate S is calculated using an arbitrary normalization factor and assuming a power law spectrum with a range of values for the integral spectral index γ, from 1 to 2.* Then, if N is large, the MDF is that flux which gives a 4.5σ effect, i.e., $(S-N)/\sqrt{N} = 4.5$. If the noise is small ($<$ 1 event per year), the MDF is calculated to be that which yields 10 events per year. These criteria are similar to those used in x-ray and γ-ray astronomy.

In Fig. 4(a) the MDF for DUMAND, normalized for convenience as the flux above 1 TeV, is shown as a function of threshold energy E_T, for $\gamma = 1.5$. Both point and diffuse sources are considered, where the angular size for the latter is taken to be $20^o \times 70^o$, approximately the area of the central region of our galaxy. We observe that the optimum E_T is not the lowest possible energy. This somewhat surprising result is explained

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*As discussed below, the neutrino spectral index is expected to be comparable to that of cosmic rays at their source. Correcting for rigidity-dependent leakage from the galaxy, this is estimated by Silberberg and Shapiro[6] to be $\gamma = 1.4 \pm 0.1$.

as follows. While the signal S, and hence the statistics, decreases with increasing energy, the ratio S/N increases and there is an optimum threshold energy E_T which is not at the place of maximum signal. Rather it is where the noise drops below 1 event per year in the specified angular window, around 1 TeV. This has the implication that other neutrino detectors (e.g., those in mines) which have a lower energy threshold than DUMAND are inherently less sensitive per unit volume to the power law spectra we have considered. Even though they may have more events per unit volume, the signal-to-noise ratio is much worse. On top of this advantage, DUMAND is much bigger as well.

In Fig. 4(b) the MDF for both discrete and diffuse sources is shown as a function of γ. The dependence on γ is not strong, but a flatter spectrum is somewhat better.

The dependence of the MDF on array size is indicated in Fig. 5 at the optimum threshold energy of 1 TeV and a range of spectral indices $1 < \gamma < 1.8$. We note the flattening of the curve as the array volume increases. This is a result of the less important role of the volume outside the array as the array gets larger. We see that, once DUMAND with a volume of $3\text{x}10^7$ m^3 is built it will not be practical to improve by an order of magnitude without going to some other technique and making major advances in the ability to measure neutrino direction, energy or other parameters.

The result is that the MDF of the proposed array is about $2\text{x}10^{-10}$ cm^{-2} s^{-1} above 1 TeV when the experimental theshold is set at 1 TeV. We estimate that this is at least three orders of magnitude lower, i.e., more sensitive, than any previous or existing underground detector.

Electron neutrinos rarely produce muons. They must be detected by light from the e-m and hadronic cascades in the reaction $\nu_e N \rightarrow eX$. To reconstruct the direction of the neutrino requires a much more closely spaced array of detectors than proposed for DUMAND. For comparison, we consider such a detector, which necessarily would have to have a reduced volume for economic reasons. Taking this to be $1.8\text{x}10^6$ m^3, the MDF for ν_e detection is also shown in Fig. 4. It is almost two orders of magnitude less sensitive than the proposed array, except in the less likely case of a very steeply falling spectrum. Arrays optimized for each type of neutrino would be nicely complementary, but it is clear that there exists an almost general principle that Cerenkov arrays are inherently more sensitive to extraterrestrial ν_μ than ν_e. For a given number of sensor units, a muon array can be much larger than one designed to measure the direction of cascades with any precision. But even for an array of a given size, if the source has a spectrum typical of cosmic rays, that source will be more readily detectable in TeV ν_μ's than in GeV ν_μ's or ν_e's of any energy, even though it is emitting more neutrinos in the latter cases.

In short, the DUMAND design represents about the most sensitive way to detect extraterrestrial neutrinos at moderate cost.

THE PRODUCTION OF VERY HIGH ENERGY NEUTRINOS AND GAMMA RAYS BY COSMIC SOURCES

The calculation of the emission of high energy neutrinos and gamma rays from cosmic sources is a challenging task for astrophysics. Basically these calculations reduce to questions of energetics and efficiencies.

First one must argue that the source has within it a powerful particle production and acceleration mechanism which generates high energy protons. Then there must be sufficient matter between us and the source so that a large fraction of these protons give up their energy to neutrinos. The latter happens by collisions producing pions and other mesons which decay into neutrinos. Thus the target matter must not be so dense as to cause these mesons to interact before decaying.

The standard cosmic ray transfer equations proposed by Ginzburg and Syrovatskii[7] and now commonly used in the one-dimensional approximation to study the propagation of cosmic ray nuclei in the galaxy[8], the production of muons in the atmosphere[9] and similar phenomena, have been used to compute the gamma rays and neutrinos emitted by high energy protons passing through matter.

A power law spectrum of protons is assumed to pass into a region of matter of uniform matter density ρ gcm^{-3} and column density (or thickness) z gcm^{-2}. The charged and neutral pion emission rates are computed from their transfer equations, assuming Feynman scaling in the fragmentation region. The muon and neutrino emission which results from the decay $\pi \rightarrow \mu\nu$ and the gamma ray emission from $\pi^0 \rightarrow \gamma\gamma$ are calculated from these pion emission rates. The muon emission is used to compute the muon neutrino emission from $\mu \rightarrow e\nu\nu$, which is added to that from pion decay. Kaon, hyperon, or charmed particle decays are expected to produce only a small fraction of neutrinos compared with pion decay and have not been considered at this time.

A very elegant simplification of this procedure was proposed by Berezinsky and Volynsky[10] in which the particle fluxes which result at the end of a chain of production and decay processes are products of easily calculable factors ϕ, called emission coefficients, which depend only on the spectral index of the primary particle flux, γ. For example, the rate of emission of ν_μ's of energy E from $pp \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow \nu_\mu$ is

$$N_{\nu_\mu}(E) = \phi_\pi(pp\rightarrow\pi^+X)[\phi_{\nu_\mu}(\pi\rightarrow\mu\nu)+\phi_\mu(\pi\rightarrow\mu\nu)\phi_{\nu_\mu}(\mu\rightarrow e\nu\bar{\nu})]N_p(E)$$

where $N_p(E)$ is the proton source spectrum. Many of the ideas and some of the numbers from Ref. 10 have been used in this calculation. However, this factorization principle is only valid in the limit of large z and small ρ: $z > 250$ gcm^{-2}, $\rho < 10^{-8}$ gcm^{-3}, as we have determined. We have considered the actual dependence on z and ρ since this is the type of information one would like to determine about a source. Thus the transfer equations must be solved numerically. In the above limits, our quantitative results do not differ significantly from those of Berezinsky and Volynsky[8].

For the present discussion, we will assume a proton energy luminosity $L_p = 10^{38}$ erg s^{-1}, which corresponds to a proton emission above 1 TeV of 1.4×10^{37} s^{-1}. The results can be scaled for any other luminosity. We present N_ν and N_γ, the rates of muon neutrinos and gamma rays, respectively, emitted from a point source. To get the flux at earth from a source at a distance R, divide by $4\pi R^2$ and multiply by any beaming factor which may characterize the emission. For simplicity, we take this to be unity.

In Fig. 6 the muon neutrino emission as a function of thickness z in the range 1 to 2 TeV is shown for $\rho = 10^{-5}$ and $\rho < 10^{-8}$ gcm^{-3}. The gamma emission, also shown, is independent of ρ. We see that the neutrino emission increases with z, flattening out above about 100 gcm^{-2}. For matter densities above 10^{-8} gcm^{-3} the resulting neutrino emission is supressed by the interaction of pions before they have a chance to decay. For low matter densities the neutrino emission builds up to an appreciable fraction of the incident proton flux (a few percent) after passing through about 10 gcm^{-2} of matter. The gamma ray emission peaks about about 40 gcm^2, falling beyond that point as the gammas are absorbed (the radiation length is taken to be 64 gcm^{-2}).

The dependence of the neutrino emission on matter density ρ is shown in Fig. 7 for two values of z, illustrating how higher densities decrease the flux as the pions interact before decaying.

The neutrino and gamma ray differential energy spectra are given in Fig. 8. The slope of the neutrino spectrum from low matter density sources corresponds to an integral spectral index of 1.5, slightly steeper than the primary proton spectrum which is taken to be $\gamma = 1.3$. For matter densities above $\rho = 10^{-8}$ gcm^{-3} the neutrino spectrum is steeper still. This effect is observed for cosmic ray muons produced in the earth's atmosphere. The gamma ray spectrum has the same slope as the primary spectrum. This, incidently, illustrates an important advantage of gamma ray observations over normal cosmic rays - the ability to determine the source spectrum. Various processes such as leakage from the galaxy tend to steepen the slope of the cosmic ray spectrum observed at earth.

As we see from these figures, the neutrino emission measured from a source will be a sensitive function of the density of the matter surrounding that source and its thickness. The gamma ray emission is essentially independent of density but a strong function of thickness. Thus a combination of the two measurements determines both. This is illustrated in Fig. 9 where contours of constant ρ and z are plotted as a function of ratio of measured neutrino and gamma ray fluxes above 1 TeV and the spectral index of the observed neutrino flux, assuming only hadronic sources of gamma rays and no other losses such as $\gamma\gamma$ interactions in regions of high photon density. Note that for sufficient thickness of matter the neutrino flux might be orders of magnitude greater than the gamma flux. Of course the opposite can also be true for a thin shell of extremely dense matter.

If we take the optimum situation, where the matter density $\rho < 10^{-8}$

gcm^{-3} and column density $z \geq 50$ gcm^{-2}, we can express the neutrino emission in terms of the proton source spectrum as

$$N_\nu(E) = .03N_p(E)\ s^{-1}\ TeV^{-1}$$

That is, the efficiency for neutrino generation is 3%. In terms of the proton luminosity L_p in erg s^{-1}, the neutrino emission above 1 TeV is

$$N_\nu\ (>1\ TeV) = 2x10^{-3}L_p\ \ s^{-1}$$

Possible Sources of Neutrinos

In evaluating the possibilities for DUMAND to observe extraterrestrial sources we have used the above formula for three classes of sources and some special cases:

1. Binary Pulsars. Cygnus X-3, possibly a neutrino star in a binary system, has been observed to be a remarkably strong sporadic source of very high energy gamma rays (>1 TeV); e.g., in October 1980 the flux[11] was $9x10^{-11}$ $cm^{-2}s^{-1}$. Its luminosity in TeV gamma rays is estimated at 10^{38} ergs/sec. Based on the considerations of the previous section the neutrino flux might be similar, which would place it just about at the threshold of detectability in DUMAND. Other such sources within our galaxy may be detectable as well.

2. Pulsars in Supernova Shells. Berezinsky and Prilutsky[12] and Berezinsky[13] explored the acceleration of particles at a newly formed pulsar and particle interactions in the dense shell of the young supernova remnant during the first half year. Theoretical calculations[14] suggest that much of this power output goes into ultra-relativistic particles.

3. SS433. Eichler[15] has pointed out that SS433 may be a particularly powerful source of neutrinos. This object is considered to be an accreting neutron star. Begelman et al.[16] estimate that the power output is $\sim10^{41}$ ergs/s.

4. Galactic Center. The galactic center could be a significant source of neutrinos[17]; it is a powerful source of positron annihilation radiation ($\sim10^{37}$ ergs/s)[18]. Jacobson[19] has observed a rapid time variation of this flux. Lingefelter et al.[20] found that a model with an ultra-massive accreting black hole explains the observations.

5. Active Galactic Nuclei. Among the extragalactic sources of neutrinos, active galactic nuclei are the most intriguing[21]. Neutrino observations can help distinguish between black hole and spinar models[22]. Rapid acceleration occurs in the accretion disk of a black hole and the density is high enough for most cosmic rays to suffer nuclear collisions[23].

6. Quasars. Large outbursts of energy $\sim10^{57}$ ergs occur occasionally in quasars. The production of neutrinos in such events has been explored by Scott et al.[24] and Eichler[25]. A recent calculation predicts a neutrino flux from 3C273 of $1\text{-}3x10^{-10}$ cm^{-2} s^{-1} above 1 TeV, right at the threshold of DUMAND[26].

In Table 1 we list the cosmic ray luminosities for these sources, as estimated in the various references. While these values are generally obtained from observations at lower energies, there are both observational and theoretical reasons for believing them to be valid at TeV energies. Observations on quasars and other active galaxies indicate that the electromagnetic luminosity per decade of energy (or frequency) is roughly constant. This implies an E^{-2} differential particle spectrum, the functional form which is predicted by many acceleration models.

Table 1. Cosmic ray luminosities of various sources.

Source or source type	L_p (ergs/s)
Binary Pulsar	10^{36} - 10^{38}
Pulsar in SN Shell	10^{41} - 10^{43}
SS433 (3 kpc)	10^{41}
Galactic Center	10^{40}
Active Galaxy	10^{44} - 10^{47}
Cen A (4 MpC)	$2x10^{44}$
3C273 (900 Mpc)	10^{46}

In Fig. 10 the resulting neutrino emission is shown as a function of the distance R to the source. Assuming the emission is isotropic, the sources which fall above the diagonal line, corresponding to $4\pi R^2$xMDF, are, in principle, detectable by DUMAND. Any beaming effects, which in fact seem to characterize most of these sources, would serve to enhance the flux above our estimates (for those sources pointing our way).

Supernovae in our local cluster of galaxies, perhaps one every five years, could be seen by a DUMAND array, assuming they emit high energy neutrinos in the manner suggested. Signals at the threshold of detection for the weak but close active galaxy Centaurus A and quasar 3C273 are indicated in Fig. 10. The predicted flux from SS433 falls well above the line, but here might be an example where beaming effects are important since the optical jets observed from this source are at least 60° from the line-of-sight.

In addition to these localized sources, it is possible to make a conservative estimate of the neutrino flux expected from the interaction of the high energy cosmic rays circling the galaxy and the gas of the galactic disk. Using the cosmic ray flux measured at earth, a neutrino flux of $2x10^{-10}$ $cm^{-2}s^{-1}$ above 1 TeV is predicted[27], just about at the level of detectability in DUMAND.

Thus it appears that there are candidate sources with sufficient energy to be detected with DUMAND, provided the other conditions for neutrino production discussed above are met. As we have seen, among these conditions are: matter density ρ not much above 10^{-8} gcm^{-3} and column density z greater than about 10 gcm^{-2}. As one example which seems to meet these conditions, a typical supernova is estimated to have and envelope with a radius of about $5x10^{13}$ cm and a matter density of about ρ =

10^{-8} gcm^{-3} during its early stages[28]. In another important case, the nuclei of active galaxies are estimated to have hydrogen column densities exceeding the radiation length in the accretion disk which surrounds the central black hole, in the black hole model, and considerably less in the magnetoid model[22,23].

CONCLUSIONS

Very high energy gamma ray astrophysics is closely related and complementary to very high energy neutrino astrophysics. The proposed undersea Cerenkov neutrino telescope DUMAND will have a sensitivity to neutrino fluxes above 1 TeV which is comparable to the sensitivity of exisiting atmospheric Cerenkov gamma ray telescopes to gamma rays of that energy. The efficient generation of neutrinos by an astronomical object requires a source of protons, or nuclei, of very high energy passing through at least ~5 gcm^{-2} of matter with a mass density $\rho < 10^{-8}$ gcm^{-3}. Gamma rays will also be produced by the same processes, but will be severely attenuated if the column density exceeds ~100 gcm^{-2}. Measurements of the relative gamma ray and neutrino flux above 1 TeV, and their spectra, provide information on the matter surrounding a source.

There are good reasons to expect that the conditions for neutrino production, including an adequate flux of protons, exist in a number of sources: binary pulsars in our galaxy, supernova shells in our galaxy and the local cluster, nearby active galaxies such as Cen A, and quasar 3C273. The center of our own galaxy is also a strong possible source.

An international collaboration of scientists from the U.S., Japan, Germany, and Switzerland has prepared a proposal for a five year program to deploy and operate the DUMAND array at a depth of 4.5 km near the coast of the island of Hawaii.

ACKNOWLEDGEMENTS

This work was partially supported by the U.S. Department of Energy. The material presented on DUMAND is based on the work of many people in the International DUMAND Collaboration. I am grateful particularly to A. Koide for his early help, to J.G. Learned for useful suggestions, and to M. Shapiro and R. Silberberg for providing some of the material and references on possibile neutrino sources.

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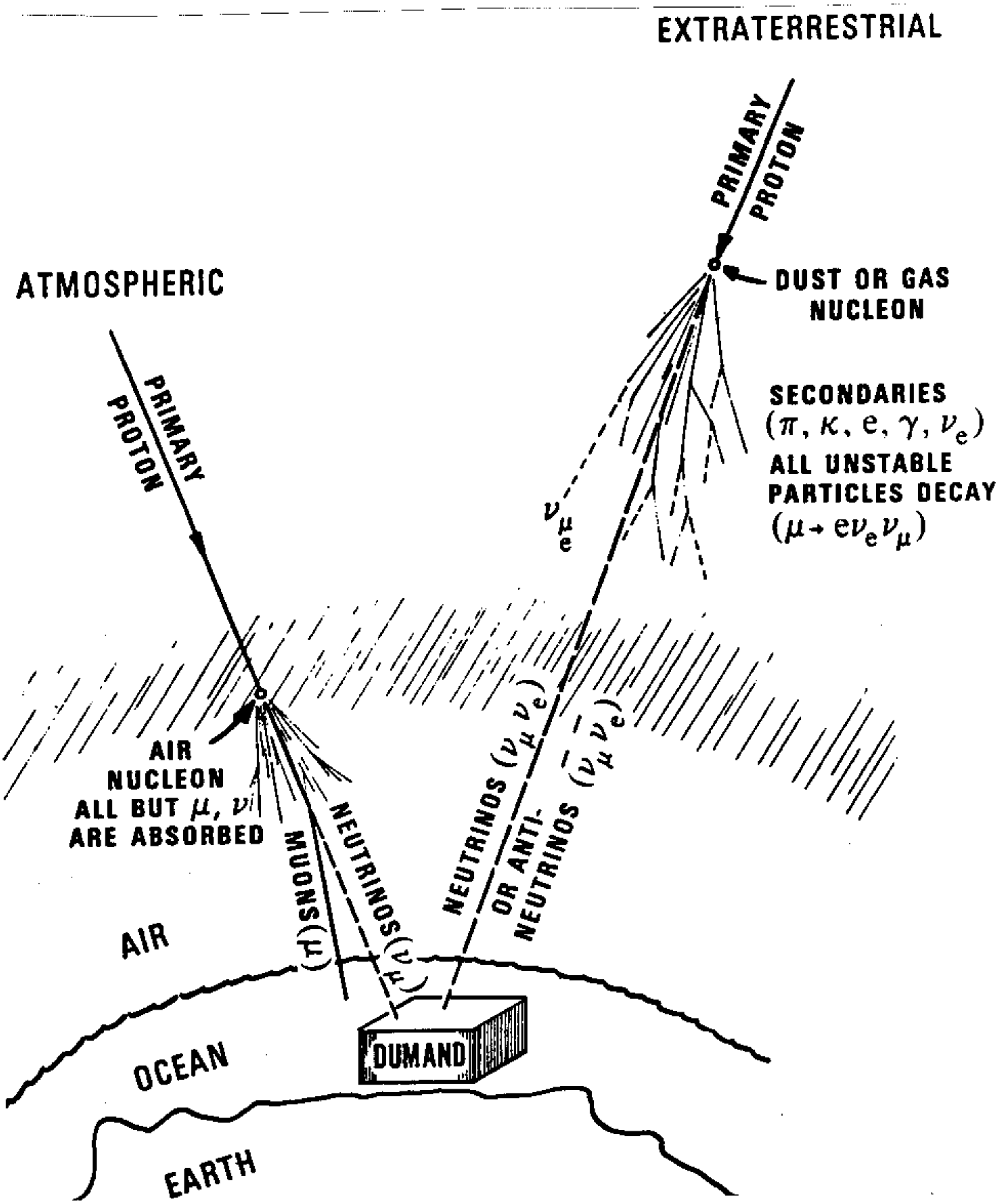

Fig. 1. The concept of the DUMAND experiment. Cosmic ray protons (or other nuclei) of very high energy strike matter, either in the earth's atmosphere or elsewhere in the cosmos. The hadronic secondaries which are produced decay into neutrinos which penetrate to the DUMAND array and are detected. Muons produced in the atmosphere with energy greater than 3 TeV can also be detected and analyzed. From the DUMAND Omnibus Proposal[29].

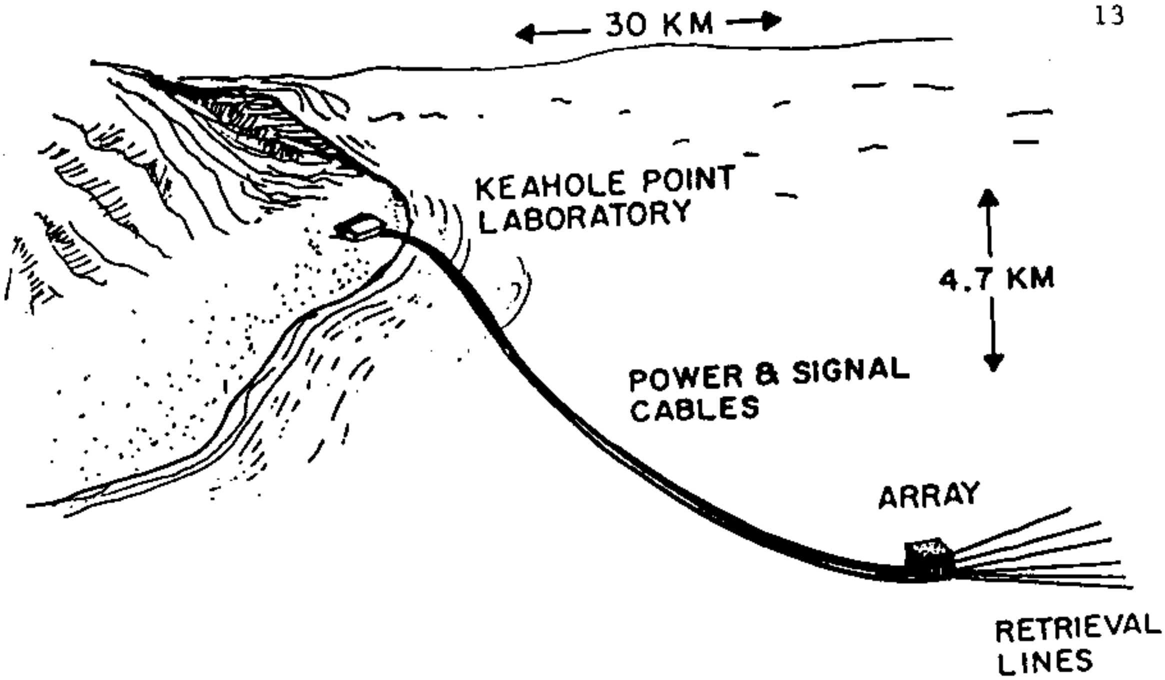

Fig. 2. Disposition of the DUMAND detector at 4.7 km depth in subsidence basin ~25 km off Keahole Point, island of Hawaii. Armored cables carrying power and fiber-optics communication connect DUMAND to the shore station. From the DUMAND Omnibus Proposal[29].

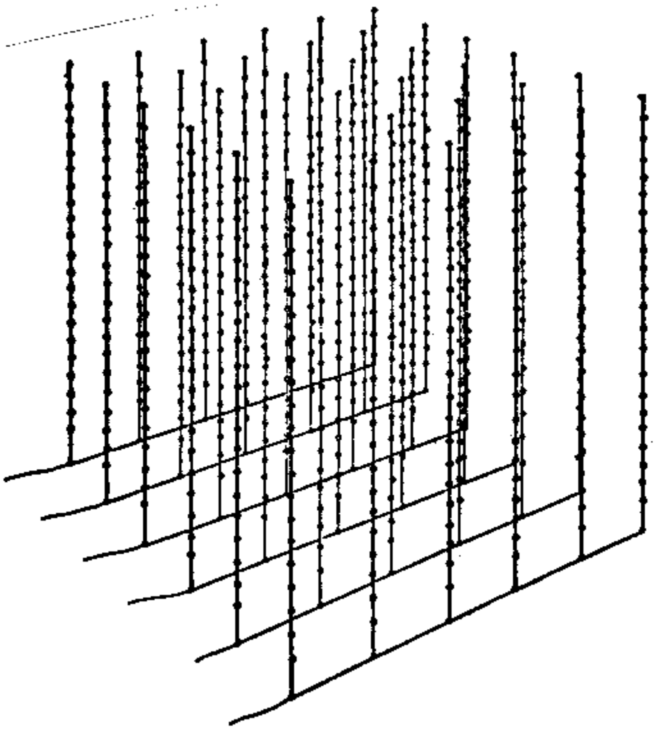

Fig. 3. The DUMAND Array. There are 36 strings, each anchored at the bottom, and held taut by a flotation module. They are spaced 50 m apart, in a 6x6 square. Along each string there are 21 detector modules spaced 25 m apart. The strings are independent--they are connected at the bottom. From the DUMAND Omnibus Proposal[29].

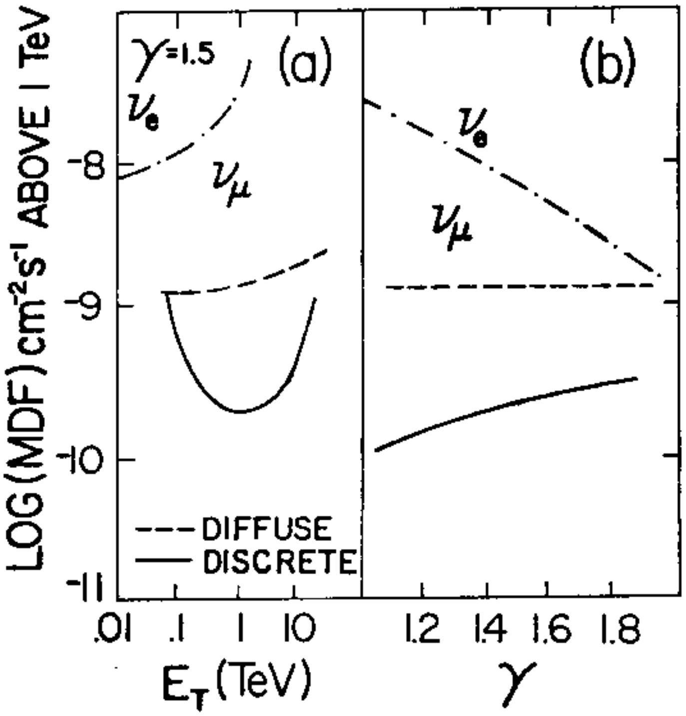

Fig. 4. The minimum detectable flux for both discrete and diffuse sources, as a function of (a) threshold energy E_T and (b) integral spectral index γ. In (b) the value of E_T is the optimum in each case. The lower curves are for the proposed DUMAND array of volume $3.1 \times 10^6 m^3$, solid curves for discrete sources, dashed curves for a $20^o \times 70^o$ diffuse source. The upper curves are for an array of volume 1.8×10^6 m^3 optimized for ν_e detection. There is no difference between these types of sources for ν_e.

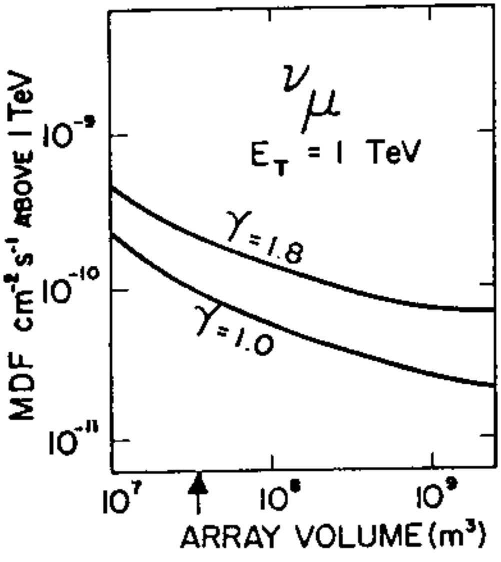

Fig. 5. The minimum detectable flux for ν_μ as a function of array volume, for integral spectral indices $\gamma = 1.0$ and 1.8. The arrow indicates the volume of DUMAND.

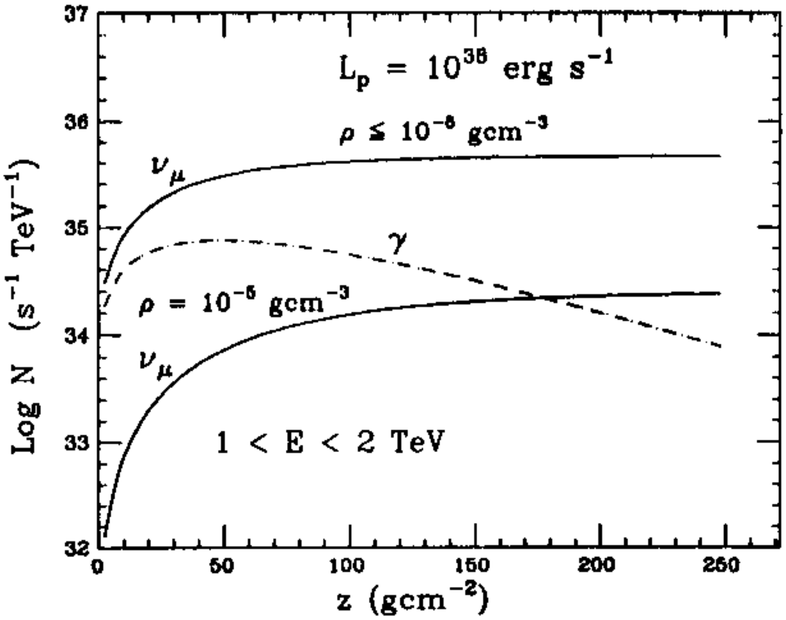

Fig. 6. The muon neutrino and gamma ray emission in the energy range 1 < E < 2 TeV for a point source of proton luminosity 10^{38} erg s^{-1} surrounded by a shell of matter density ρ, as a function of the thickness z. The curve labelled γ is the γ ray emission, which is independent of ρ.

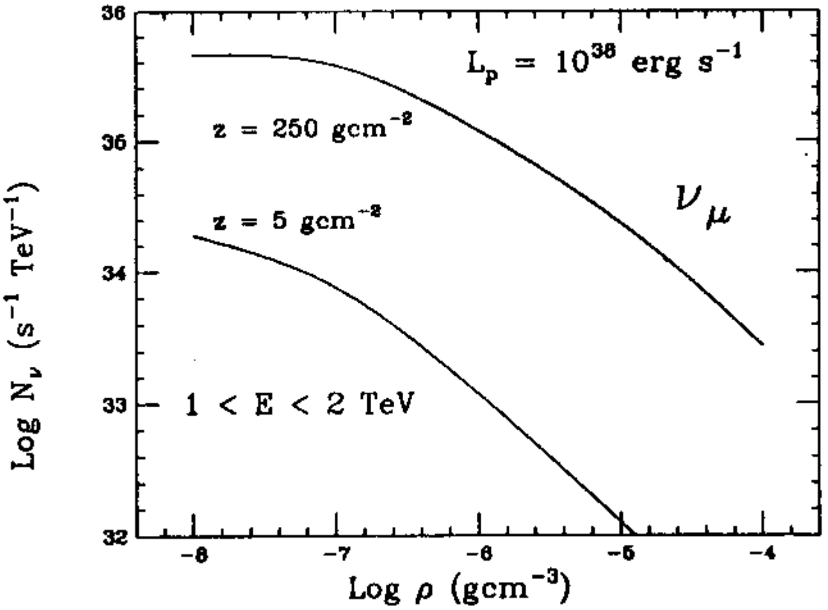

Fig. 7. The muon neutrino emission in the energy range 1 < E < 2 TeV for a point source of proton luminosity 10^{38} erg s^{-1} surrounded by a shell of matter density ρ, as a function of ρ, for two values of the thickness z.

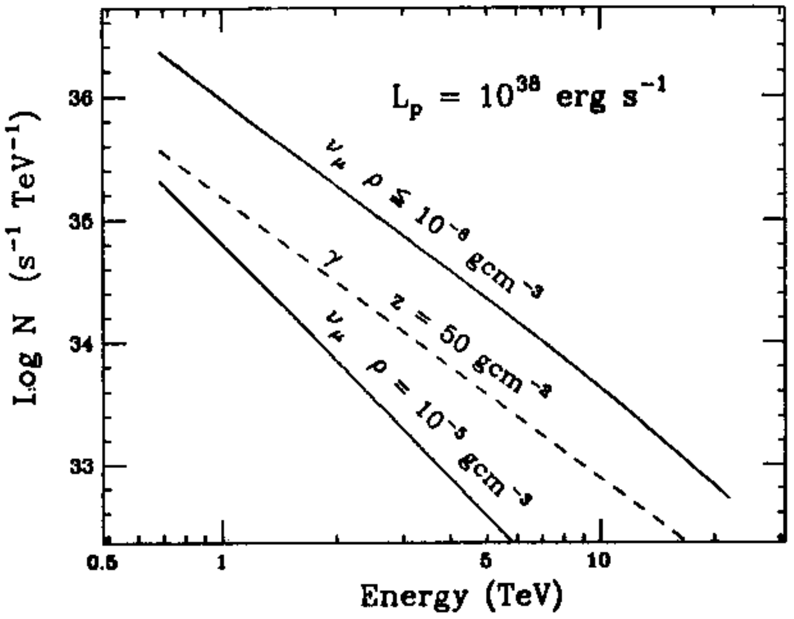

Fig. 8. The muon neutrino (solid) and gamma ray (dashed) emission spectra for a point source of proton luminosity 10^{38} erg s^{-1} surrounded by a shell of matter density ρ and thickness z.

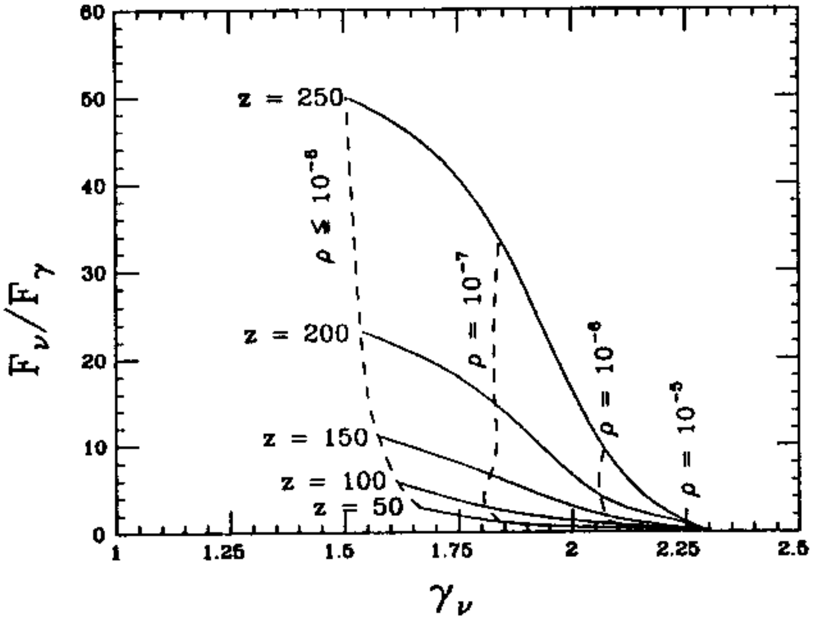

Fig. 9. Contours of constant matter density ρ (in gcm^{-3}) and thickness z (in gcm^{-2}) in the plane of the ratio of muon neutrino and gamma ray fluxes and neutrino integral spectral index γ_ν. The proton source spectrum has a spectral index $\gamma = 1.3$.

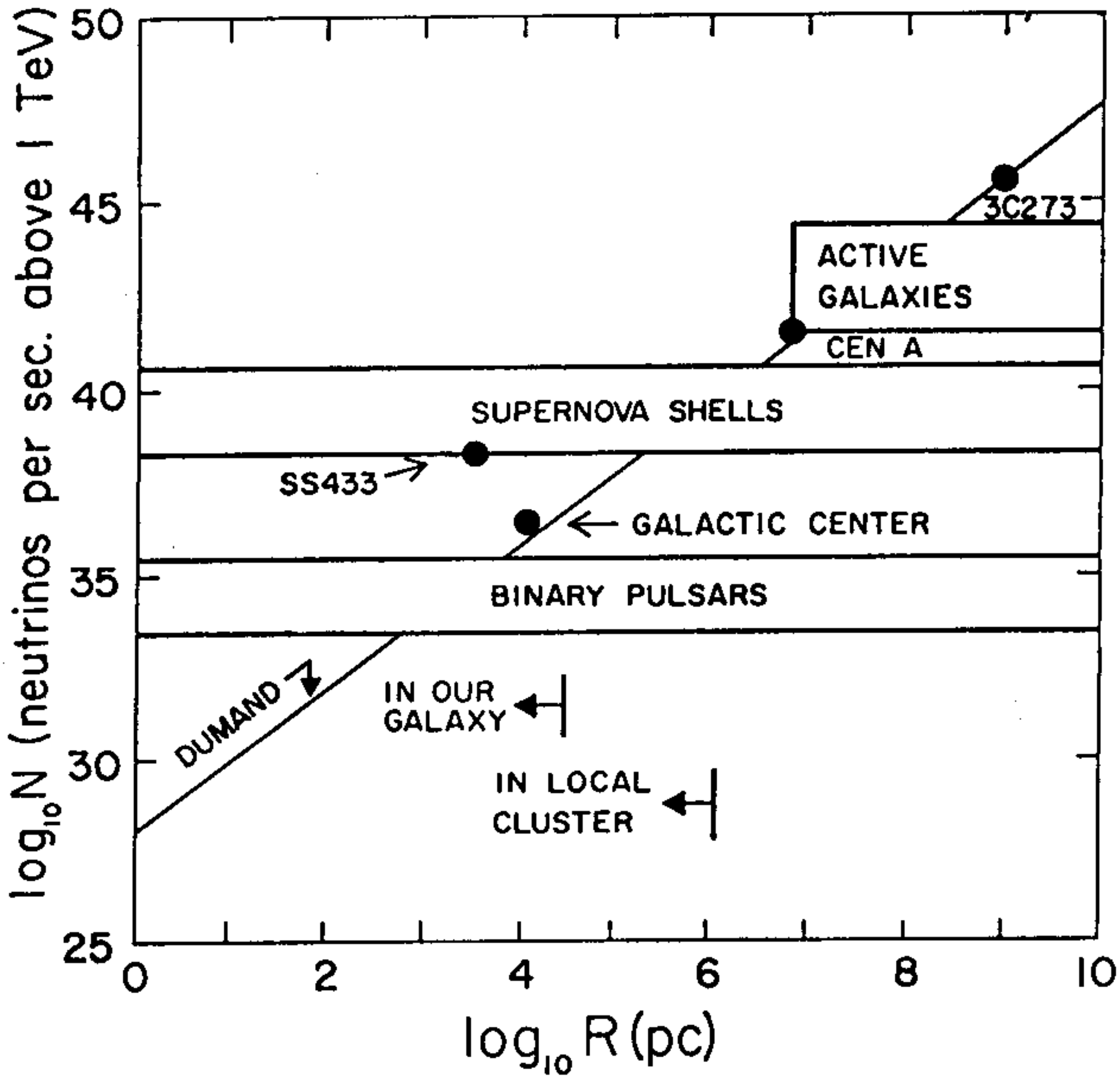

Fig. 10. The extraterrestrial source detection capabilities of the DUMAND array. Shown is the source intensity in neutrinos per sec. above 1 TeV vs. distance R in parsec. The bands indicate the range of different source types. The points are specific sources. Anything above the diagonal lines is detectable.