

NEUTRINO AND GAMMA-RAY ASTRONOMY IN THE SEA

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The DUMAND proposal to place an array of 216 photomultipliers at a depth of 4.7 km in the ocean off the island of Hawaii has received the endorsement of the U.S. High Energy Physics Advisory Panel. This array, called the Octagon, will have an effective area for muons from astronomical neutrinos of $20,000 \text{ m}^2$ and an angular resolution of 1° . Because of its location and depth, the Octagon will have 100% sky coverage. It is anticipated that cosmic sources of very high energy particle acceleration, such as Cygnus X-3 and Hercules X-1, will be detectable by the neutrinos, and possibly also by the γ -rays, emitted by these sources. The capabilities of underground and underwater muon detectors to detect muons from cosmic γ -rays is estimated. It is shown that, if very high energy γ N interactions in the atmosphere produce anomalous muons at least 3% of the time, the DUMAND Octagon will be large enough to detect γ -rays at currently observed flux levels.

1. INTRODUCTION

The Deep Underwater Muon and Neutrino Detector (DUMAND) has now received the endorsement of the High Energy Physics Advisory Panel (HEPAP) to move on to its second phase. The successful completion of the first phase, the Short Prototype String, will be described by the following speaker. The DUMAND collaboration* has proposed to next deploy a nine string array of 216 photomultiplier tubes. This array, dubbed the Octagon, will have an effective area of $20,000 \text{ m}^2$, angular resolution of 1° , and some ability to discriminate energy by measuring dE/dx .¹ Detectable neutrinos from sources such as Cygnus X-3 will occur, provided that the neutrino flux is enhanced by at least a factor of three over the observed γ -ray flux above 1 TeV. Such an enhancement is highly plausible,² with some models predicting even more.³ The Octagon will be more sensitive than any existing or planned underground detector, and comparable in sensitivity to GRANDE. The range of possible

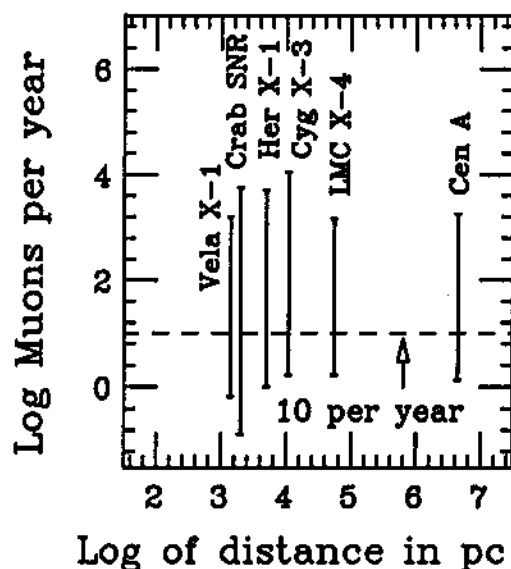


Fig. 1. The range in the signal, in muons per year, from several possible neutrino sources, as a function of distance. The lower limits assume that the neutrino flux equals the observed γ -ray flux from each source. The upper limits are based on existing experimental limits.⁴

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event rates for some sources that have been observed to emit γ -rays above 1 TeV is indicated in Fig. 1. The upper limit of some 100's of events per year is based on existing experimental limits.⁴

An important and unique feature of DUMAND will be its essentially 100% sky coverage. Because of its great depth, DUMAND will be able to search for muons from neutrinos up to 20° above the horizon. This occurs about 50% of the time for Cygnus X-3 and other prominent candidate sources, such as Hercules X-1, in the declination range $-0.5 < \sin \delta < 0.9$ (see Fig. 2). Sources in the Southern Hemisphere, such as LMC X-4, can be watched essentially 100% of the time.

For Cygnus X-3, it will also be possible to search half of the time for muons that may be produced by γ -rays, when the source is above 20° (see Fig. 3). This report will focus on the sensitivity of the Octagon to these γ -rays and the rationale for such a search.

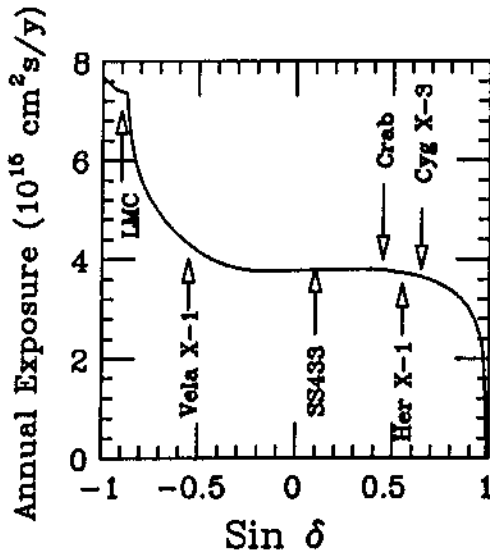


Fig. 2. The annual exposure of the Octagon as a function of declination of the source. Several potential sources are indicated.

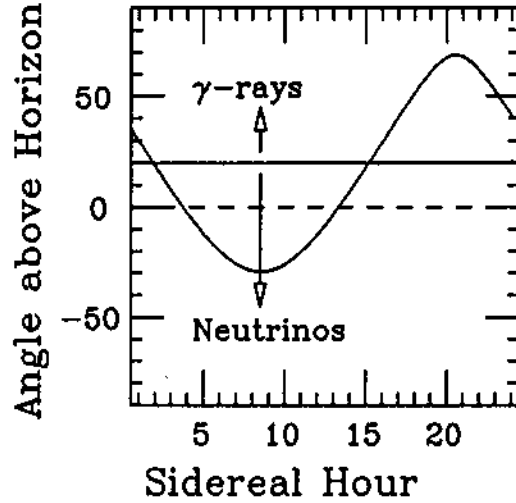


Fig. 3. The path of Cygnus X-3 at the DUMAND site in the course of a sidereal day. Below 20° elevation, we look for muons from neutrinos. Above 20° , we can look for muons from γ -rays.

2. DETECTION OF MUONS FROM GAMMA RAY SOURCES

In the case of point source neutrinos, DUMAND is essentially signal-limited. Below 20° elevation, the background will be less than one event per year in a 1° circle on the celestial sphere. In this case, a signal of ten events per year is detectable. At higher elevations, however, the cosmic ray muon flux will be large and source detection capability will be background-limited. In this case, the signal S can be searched for above the fluctuation in the mean of the background flux B , using the criterion:

$$\frac{S + B - \langle B \rangle}{\sqrt{\langle B + 1 \rangle}} > 4.5 \quad (1)$$

In the case of Cygnus X-3, $\langle B \rangle = 422 \text{ y}^{-1}$ and a signal $S = 422 \text{ y}^{-1}$, or $S/B = 1/20$, is thereby detectable.

If the muon spectrum from the source is flatter than that for the cosmic ray background, it is possible to make a $\langle dE/dx \rangle$ cut that improves the sensitivity by about a factor of two. In any case, for the source to be detectable by this means, the particles from that source (presumably γ -rays) must be capable of producing a muon flux of the order of $10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ above 1 TeV at sea level. This is to be compared with the reported γ -ray flux of $4 \times 10^{-12} \text{ s}^{-1}$ above 1 TeV from Cyg X-3.⁵ Such a flux of γ -rays would be detectable by DUMAND provided the ratio of fluxes is greater than $\mu/\gamma = 0.025$.

Fig. 4(a) shows the simulated signal and background DUMAND would observe as a function of sidereal time in one year's observation, assuming the signal is just a detection threshold. Fig. 4(b) shows the variation in the quantity defined in (1). Note the 5σ peak at a zenith angle of 60° , where the high slant depth results in a filtering out of more background than signal because of the latter's flatter spectrum.

3. PRODUCTION OF MUONS BY GAMMA RAYS

The next question that must be explored is whether it is reasonable to expect as much as 2.5% muon production by γ -rays at the high energies involved here. Muons are produced normally by γ -rays by the decay of pions and other mesons produced in γN interactions. At accelerator energies, the cross section for this process is of the order of $100 \mu\text{b}$. This is to be compared with the electron pair production cross section for γ -rays in air which is of the order of 500 mb . Thus $\mu/\gamma < 2 \times 10^{-4}$ is expected (I am ignoring cascade effects which will produce lower energy muons not able to penetrate to DUMAND depth).

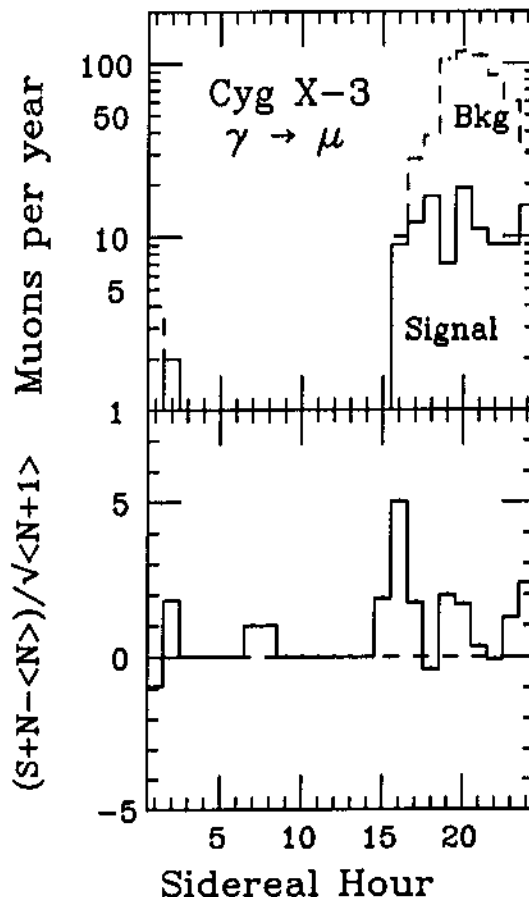


Fig. 4. The number of muons per year in background and signal (a) and fluctuation of the signal (b), for a signal just at the detectability threshold, as a function of sidereal hour.

It has been pointed out that QCD effects could increase the γN cross section at very high energies.⁶ However these are unlikely to increase the cross section much over 1 mb leaving $\mu/\gamma \sim 10^{-3}$. About another factor of ten is needed.

The spectrum of muons from pions and kaons produced in the atmosphere is steeper by one power in energy than the spectrum of the primary particles. This does not happen for those muons from heavy flavor decay, which will follow the primary spectrum since the decay lifetime is short. Thus, at some energy around 10-100 TeV muons from these prompt decays

will dominate. In QCD, $c\bar{c}$ production is about 1/10 of $u\bar{u}$, and $c \rightarrow \mu$ about 1/10 of the time, so this mechanism will also be inadequate.

4. THE MUON ANOMALY

In short, conventional physics, including QCD, does not appear adequate to produce flux of muons produced by γ -rays from sources such as Cygnus X-3 that would be detectable by current or planned underground or underwater experiments. However, reports persist that excess muons are being produced by the γ -rays, or whatever the ultra-high energy particles, coming from Cygnus X-3 and Hercules X-1.⁷ If this muon anomaly is confirmed, two conclusions can be drawn from the above analysis: (1) DUMAND and possibly other underground and undersea detectors will be able to detect these sources; (2) new physics beyond the Standard Model is occurring -- either in the very high energy γN interaction or the production of some new stable neutral particle in cosmic accelerators.

5. CONCLUSIONS

The DUMAND Stage 2 proposal, the Octagon array, has received the endorsement of HEPAP. This array should be capable of detecting neutrinos from very high energy cosmic accelerators such as Cygnus X-3 and Hercules X-1, provided that neutrino production is enhanced over that for observed γ -rays by about a factor of three. In addition, the γ -rays from these sources will be detectable, provided that anomalous production of muons at about the 3% level occurs in high energy γN interactions. If current reports that such anomalous production occurs at much higher levels are verified, then DUMAND and other underground or underwater muon detectors will have plenty of muons and provide a new channel for very high energy particle astrophysics.

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