

## MUONS ON THE MOON

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### ABSTRACT

Neutrino astronomy on the earth is currently signal-limited, rather than background-limited. Thus the absence of atmospheric muon background on the moon does not provide any obvious advantage in the search for point sources, although some advantage may exist for diffuse sources. A lunar detector for neutrino astronomy will still have to be as large as any on earth. The earlier suggestion that a window around 1 GeV exists, where backgrounds on earth are large, is shown to not provide for likely detectable sources.

### 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.<sup>1</sup> The DUMAND collaboration has proposed to deploy an array of 216 photomultiplier tubes at a depth of 4.8 km off the coast of the island of Hawaii. This array, dubbed the Octagon, will have an effective area of 20,000 m<sup>2</sup>, angular resolution of 1°, and some ability to discriminate energy by measuring mean  $dE/dx$  for throughgoing muons produced by the interaction of muon neutrinos in the water or earth below the array.

The Octagon will be more sensitive than any existing or planned underground detector and, unlike other detectors, will have essentially 100 percent sky coverage. 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  $\gamma$ -ray flux above 1 TeV. Such an enhancement is highly plausible, with some models predicting even more.

In thinking about any experiment on a lunar base, one must look for advantages over doing the experiment on earth. In the case of extra-solar neutrino astronomy, very high energy muon neutrinos represent by far the most promising avenue of search, first because

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\* Aachen, Bern, Caltech, Hawaii, Kiel, Kinki, Kobe, Okayama, Scripps, Tokyo, Vanderbilt, and Wisconsin

they are likely to be more plentiful, second because the cross section increases with energy, and third because the long range of high energy muons enable the material of the earth, or moon, to comprise the major portion of the detecting material. Any experiment able to detect muons will be far more sensitive than an experiment of comparable size designed to detect electrons or other particles produced by the interaction of electron neutrinos. In DUMAND the ocean provides the main detecting medium, allowing for very large detector dimensions. A detector on the moon will have to similarly rely on the moon as the main medium for detection.

On the earth, a large background of cosmic ray muons produced by primary cosmic rays hitting in the upper atmosphere exists. These will swamp any neutrino-induced muons over most of the overhead celestial hemisphere. Nevertheless, in the case of DUMAND sufficient solid angle remains to enable the experiment to explore virtually the entire celestial sphere at last half of the time. A background of upward-going muons from neutrinos produced by cosmic rays on the other side of the earth also exists, but these will be less than one per year in each one degree circle on the celestial sphere being searched for sources.

Previous studies of the possibilities for neutrino astronomy on the moon have suggested that a substantial advantage would result from the absence of these atmospheric neutrinos.<sup>2,3</sup> In particular, it was argued that, since no muon background in the range 1-1000 GeV exists on the moon, a lunar observatory could search for sources with steep spectra and fluxes too small at higher energies to be found by experiments such as DUMAND.

In this paper I basically dispute this conclusion, at least for point sources. Some advantage may exist in the search for diffuse sources, but the detector in any case will still have to be so large that neutrino astronomy on the moon can be made feasible only if the material of the moon itself can be used.

## THE DETECTION OF MUON NEUTRINOS

In Fig. 1, a plot is shown of the muon spectra that would result for muons produced in the body of the moon below a muon detector at or near the surface, for neutrinos with power-law integral spectra  $E_\nu^{-3}$  and  $E_\nu^{-1}$ . The latter is closer to what is expected from the most likely sources such as Cygnus X-3, the former is comparable to the spectrum of atmospheric muons and neutrinos on

earth. For the flatter neutrino spectrum, we see that most of the events occur with  $E_\mu > 50$  GeV and no advantage is offered by being able to search for muons down to as low as 1 GeV. The steeper spectrum, however, would appear to provide such an advantage. However, another factor must be considered.

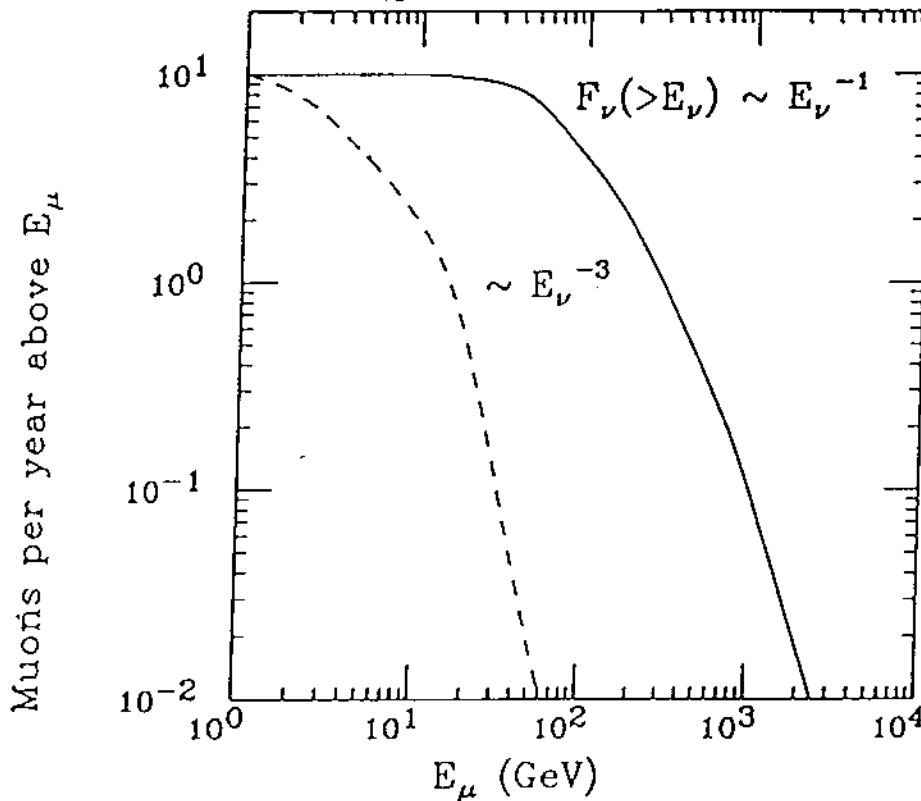


Fig. 1. The muon spectra that would be observed for muons from neutrinos produced with two different power law spectra. Both curves have been normalized to give the same number of events above 1 GeV.

In cases where the background in the region being searched for a source is negligible, a signal of ten events per year can be regarded as detectable. In Fig. 2, the minimum detectable flux of muon neutrinos from an astronomical source required to produce ten events per year is presented for a muon detector with an arbitrary average effective area of  $1000 \text{ m}^2$ . The minimum detectable flux can be scaled up or down with that area. The flux is presented as the

integral flux above 1 GeV and plotted as a function of the integral spectral index. That is, the integral neutrino flux is given by

$$F_{\nu}(>E_{\nu}) = F_{\nu}(> 1 \text{ GeV}) E^{-\gamma} \quad (1)$$

where  $E$  is in GeV.

Note that the minimum detectable flux is some six orders of magnitude greater for  $\gamma = 3$  than for  $\gamma = 1$ . That is, a muon detector of a given area has a sensitivity that is markedly better for flatter spectra than steep spectra. The reason for this large difference is the multiplying effect of the factors mentioned earlier: Both the  $\nu N$  interaction cross section and effective detector volume increase with energy.

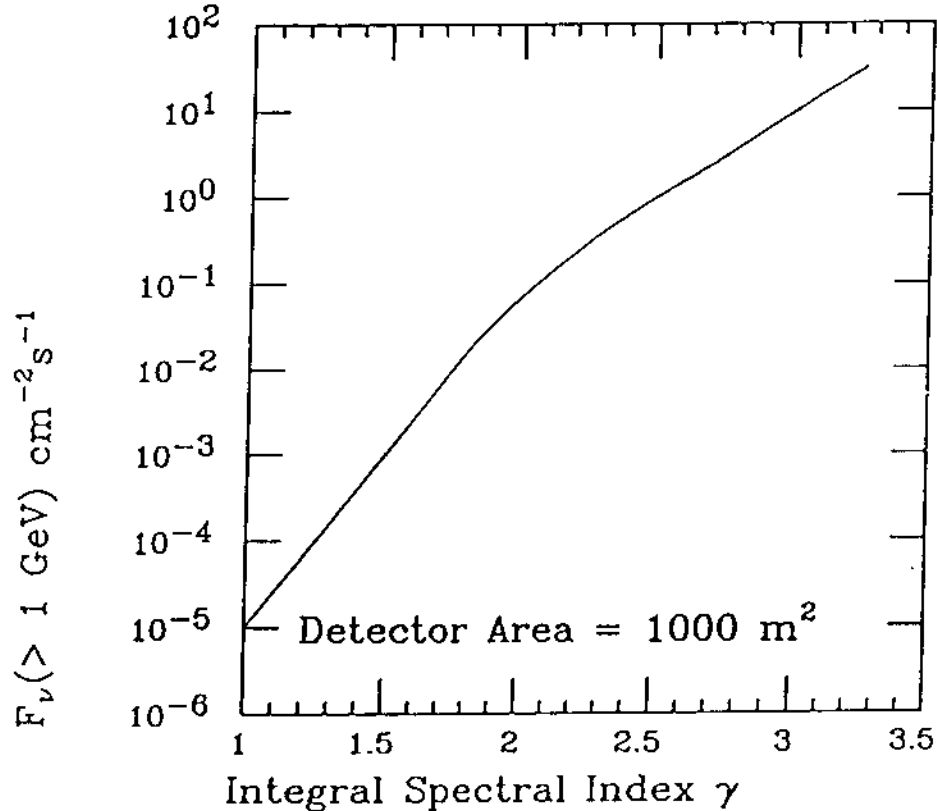


Fig. 2. The minimum detectable flux of neutrinos above 1 GeV that is required to give 10 events per year, as a function of the integral spectral index  $\gamma$ , for a detector area of 1000  $\text{m}^2$ . The required flux for other detector areas may be scaled accordingly.

Fluxes higher than about  $10^{-3} \text{ cm}^{-2} \text{ s}^{-1}$  above 2 GeV with integral spectral index  $\gamma = 2$  are already ruled out over much of the sky by previous underground experiments.<sup>4,5</sup> So the best hope for neutrino detection remains sources with flat spectra. These are also the most likely. In the search for point sources, all current and planned experiments are signal-limited rather than background-limited. However, this is not the case for possible diffuse sources, such as the galactic center. In this case, the window that must be opened on the celestial sphere will let in considerable background from atmospheric neutrinos on the earth, and a lunar neutrino observatory would have certain advantages.

With the whole Pacific Ocean available, the DUMAND array will be readily expandable to even greater dimensions, should the science warrant it. At some point, perhaps above about  $10^5 \text{ m}^2$ , the atmospheric background to point sources will become important and a lunar observatory could provide some advantages.

## BACKGROUNDS ON THE MOON

The background of muons on the moon is small, but not zero. Muons will be produced by the so-called "prompt" neutrinos that are produced in the decay of short lived particles with heavy flavor, such as charm. The pions and kaons that are primarily produced when cosmic ray protons bombard the moon interact in the rock before having a chance to decay to muons and neutrinos. However, the heavy flavor particles produced have such short lifetimes that they decay first. I estimate that the flux of upward neutrinos from heavy flavors will be about  $4 \text{ m}^{-2} \text{ y}^{-1}$  and that this will lead to an upward muon flux on the surface of the moon of  $100 \text{ km}^{-2} \text{ y}^{-1}$ . These muons will all be above several TeV.

So, the background for point sources in a one degree circle will be only about 1 per  $100 \text{ km}^2$  per year, negligible for all practical purposes. In a  $20^\circ \times 70^\circ$  region that encompasses the galactic nucleus where neutrino production is expected from cosmic rays interacting with the dense matter, the background would be  $2 \text{ km}^{-2} \text{ y}^{-1}$ , much smaller than the corresponding flux on earth.

## CONCLUSIONS

The moon offers some advantages over the earth for neutrino astronomy, but they are not so obvious. Basically neutrino

astronomy is now, and is likely to remain for some time, signal-limited rather than background-limited. The fact that the muon background is essentially zero down to 1 GeV range is of little consequence. If the neutrino spectra from astronomical sources is as flat as expected, then most of the events will have  $E_\nu > 50$  GeV where the atmospherically-produced backgrounds on earth are already small. If sources exist with steep spectra, or spectra that cut off above of few tens of GeV, the sensitivity of any muon detector will be far lower than for flat spectrum sources. Of course such sources could exist, and it may someday prove important to try to detect them on the moon. However the detector to do this will have to have an effective area average over all directions of at least 100,000  $\text{m}^2$  and maybe more.

A lunar neutrino detector would be superior to earth-bound detectors of the same effective area in the search for diffuse sources such as the galactic center. Again such sources could prove important. Perhaps an isotropic high energy neutrino background exists (the  $1/4000$  eV relic neutrinos from the Big Bang are hopeless to detect, at least by any means thought of so far). This would be of great cosmological interest. However, it is amply clear that any such detector on the moon would have to be of such great size that the detector medium could not be transported to the moon. Thus the material of the moon itself must be used, either directly or to manufacture the detector medium in great quantities. Unless glass can be made from green cheese, optical detection techniques are unlikely. Acoustic detection may be the only viable alternative.<sup>6</sup>

## REFERENCES

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