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Neutrinos from Active Galactic Nuclei

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Abstract

Active galactic nuclei (AGNs) are predicted to be intense sources of neutrinos of energies as high as 1000 TeV. The combined neutrinos from all AGNs are estimated to produce a flux of muons in the earth that exceeds the cosmic ray background for muon energies above 300 GeV. The DUMAND II array, currently under construction, would see thousands of these events per year. Such observations would not only provide a glimpse of the interior of active galaxies, but allow the study of neutrino interactions at energies two orders of magnitude higher than available at accelerators. At these energies, attenuation in the earth is appreciable and the core of the earth could be seen.

1. INTRODUCTION

In a recent calculation, Stecker, Done, Salamon and Sommers predict that the flux of high-energy neutrinos emitted by active galactic nuclei (AGNs) will be so high as to be detectable in underground and underwater experiments currently either operating or under construction.[1]

In this model, protons are accelerated in the vicinity of a massive black hole at the center of the galaxy – possibly by accretion shock, although the precise acceleration mechanism is not critical. While the model itself is not new, recent UV and X-ray data have made it possible to make more reliable quantitative predictions. The accelerated protons interact with the photon field surrounding the black hole. These photons are thought to be responsible for the observed "40 eV bump" characteristic to many AGN spectra. At an energy of about 10^7 GeV, protons interacting with 40 eV photons will produce the resonance reactions:

$$\begin{array}{llll} p + \gamma \rightarrow \Delta^+ & \rightarrow \pi^+ \; n & & \\ & \quad \downarrow\!\!\rightarrow \mu^+ \; \nu_e \; \bar{\nu}_\mu & & \\ & \rightarrow \pi^0 \; p & & \\ & \quad \downarrow\!\!\rightarrow 2\gamma & & \end{array} \qquad (1)$$

which will be expected to dominate. The γ–rays do not escape the photon field, but interact and eventually degrade in energy to produce the observed X–rays. Thus existing very high energy γ–ray telescopes would not be expected to see a signal, with only the neutrinos escaping from the central regions of the AGN.

The observation of neutrinos from active galactic nuclei would not only provide unique information on the nature of the most powerful energy sources in the universe, but comprise a sample of neutrino interactions with matter at energies at least two orders of magnitude higher than is available with current particle accelerators. Furthermore, neutrinos of such great energy will experience significant attenuation in the earth, making possible a measurement of the earth's density profile and the direct observation of the earth's core.

Here I present a calculation of the flux of muons that would exist underground from AGN neutrinos at the predicted flux levels, and the energy spectrum and zenith angle distribution expected for these muons. Some remarks are also made about their detectability in the Deep Underwater Muon and Neutrino Detector (DUMAND II) currently under construction.

2. CALCULATION OF THE MUON FLUX

Suppose a muon detector is located at a depth d below the surface of the earth. Consider a ν_μ of energy E_ν directed toward the detector that travels a distance x through the earth and then interacts. Let $Z = \int \rho dx$ be the column density of matter traversed by the neutrino, where ρ is the matter density. If σ_T is the total $\nu_\mu N$ cross section, including neutral currents, then the neutrino flux hitting the earth will be attenuated prior to the interaction point by a factor $\exp(-N_A \sigma_T Z)$, where N_A is Avogadro's number.

If the interaction is charged current, a muon of energy $(1-y)E_\nu$ will be produced, where y is the conventional Bjorken variable. Let E_μ be the muon energy at the detector, and R_μ be the mean range of a muon that starts with energy $(1-y)E_\nu$ and ends with E_μ. The average flux of muons of energy E_μ per unit energy passing through the detector at and angle θ with respect to the zenith can then be obtained from the numerical integration,

$$F_\mu(E_\mu,\theta) = N_A \int_{E_\mu}^{\infty} F_\nu(E_\nu)\, dE_\nu \int_0^{1-\frac{E_\mu}{E_\nu}} R_\mu[E_\mu,(1-y)E_\nu]\, e^{-N_A\sigma_T Z(\theta)} \frac{d\sigma_\nu}{dy}\, dy \tag{2}$$

where $F_\nu(E_\nu)$ is the differential flux of neutrinos hitting the earth and $d\sigma_\nu/dy$ is the differential cross section for $\nu_\mu N$ charged current interactions.

Note that the column density Z is a function of θ, which leads to a zenith angle dependence of the flux even when the neutrino source distribution is isotropic. The exponential technically remains inside the integral over Bjorken y since Z depends on the muon range R_μ, which depends on y.

Most underground and underwater muon detectors look for neutrinos below the horizon, where cosmic ray muons are negligible and the only known source of a signal is neutrinos. Deeper detectors, such as DUMAND, can also look somewhat above the horizon, so the zenith angle range $-1 < \cos\theta < 0.2$ has been considered. In this calculation, water density has been used above the horizon. Below the horizon, the earth density profile as a function of depth in the earth has been taken from Stacey.[2]

As already noted, the energy of neutrinos from AGNs predicted by the model are orders of magnitude higher than available from the highest energy particle accelerators on earth. Thus any estimate of νN interaction rates must necessarily be based on theory. While the Standard Model enables a fairly reliable extrapolation to higher energies, some uncertainties result from the unknown details of quark and gluon structure functions. The cross section formulas used here are those calculated by Reno and Quigg.[3] The actual observation of neutrino events from AGNs may thus provide information on very high energy neutrino interactions.

3. MUON SPECTRA AND ANGULAR DISTRIBUTIONS

The integral spectrum of muons implied by the flux given in Ref. 1 for the sum of all AGNs, integrated over the zenith angle θ, is shown in Fig. 1. This is compared with the muons expected from neutrinos produced by primary cosmic rays hitting the atmosphere. We see that the spectral shape for AGN muons is flat almost out to 10^4 GeV. Half of the muons hitting the detector have energies above 3–4x10^4 GeV. Atmospheric neutrinos, on the other hand, produce a sharply falling muon energy spectrum.

The muon energy spectra are essentially independent of zenith angle (not shown). The zenith angle dependence of the muon flux is given in Fig. 2 for muon thresholds of 1 GeV and 10 TeV, again for both AGNs and atmospheric neutrinos. The distributions are clearly not sensitive to the energy spectrum, and the extreme flatness of the AGN spectrum compared to atmospheric neutrinos is again in evidence. The non–isotropic nature of AGN muons is a direct result of the attenuation in the earth of very high energy neutrinos.

Fig. 2 is the zenith angle distribution expected from the sum of all AGNs in the Stecker et al. calculation. The distributions expected from two point sources, the Seyfert galaxy NGC4151 and the quasar 3C273 are presented in Fig. 3, again using the neutrino spectra predicted in Ref. 1. The harder spectrum of the quasar results in even greater attenuation at large zenith angles, where the neutrinos must pass through more matter to get near the detector.

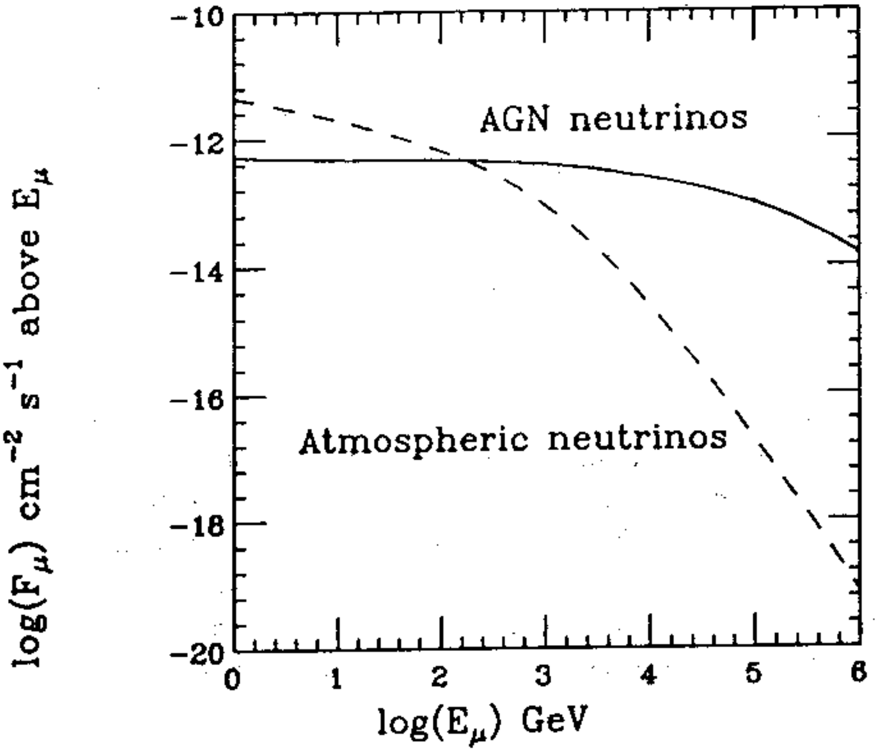

Fig. 1. Integral muon energy spectrum for a detector at a depth of 4.5 km, integrated over all zenith angles, for neutrinos from Active galactic nuclei compared with atmospheric neutrinos.

4. CAPABILITY OF DUMAND

The second phase DUMAND array now under construction for deployment in the ocean off the Big Island of Hawaii,[4] is ideally suited for the detection of neutrinos from active galactic nuclei. The effective detection area of DUMAND II as a function of muon energy is shown in Fig. 4. Folding in the expected E^{-2} neutrino energy spectrum from binary pulsar point source candidates, such as Cygnus X–3, gives an effective area of 20,000 m^2. The predicted AGN spectrum is even flatter, giving an effective area of 28,000 m^2.

The mean energy of muons in the first case is a few TeV, compared to about 15 TeV for AGNs. This also leads to a significant improvement in muon pointing accuracy, from a median error of about 1° for binary pulsar sources to 0.5° for AGNs.

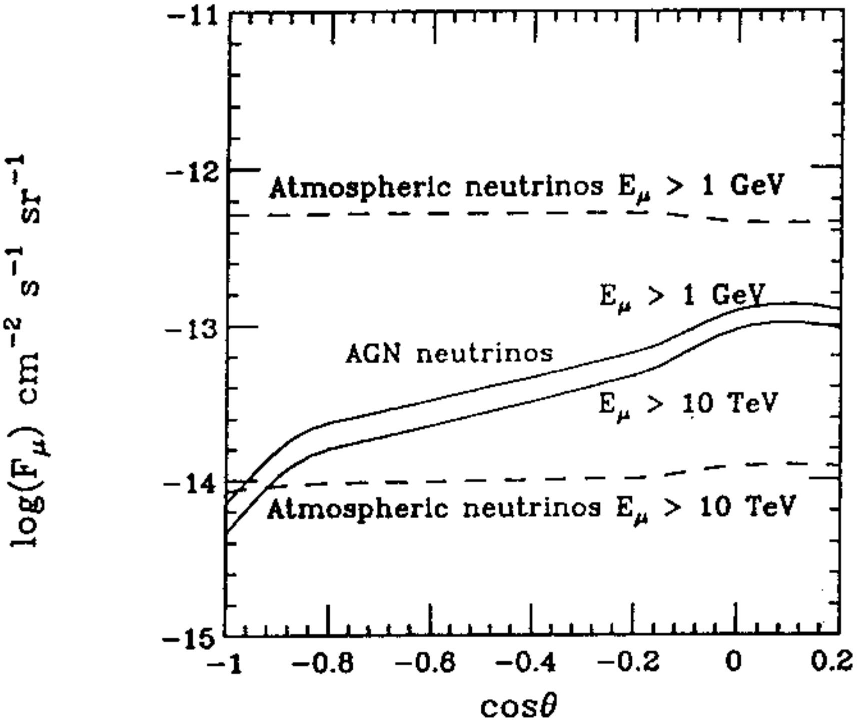

Fig. 2. Distributions in $\cos\theta$, where θ is the zenith angle of the muon, for AGN and atmospheric neutrino events, for two muon energy thresholds.

The event rates predicted for DUMAND II are 4,400 per year for the sum of all AGNs, 2 per year for NGC4151, and 0.2 per year for 3C273. It seems that the detection of point source AGNs will have to await DUMAND III. However, the event rate from the sum of all AGNs is substantial and easily detectable.

DUMAND II will be capable of detecting point sources of high energy neutrinos that produce 5–10 events per year. This is possible because of the low background of the detector, less than one event per year in each 1° pixel from atmospheric neutrinos or various backgrounds that can fake neutrino events. Diffuse sources, such as the sum of AGNs, must be distinguished from the atmospheric background. However, this can be done by measuring the dE/dx of muons traversing the array. When a muon has several TeV or greater, nuclear scattering and radiative processes produce Cherenkov light that is proportional to muon energy. Monte Carlo calculations have shown that an AGN signal can be distinguished from atmospheric neutrinos in DUMAND II at a signal–to–noise ratio of about 10% or greater.[5]

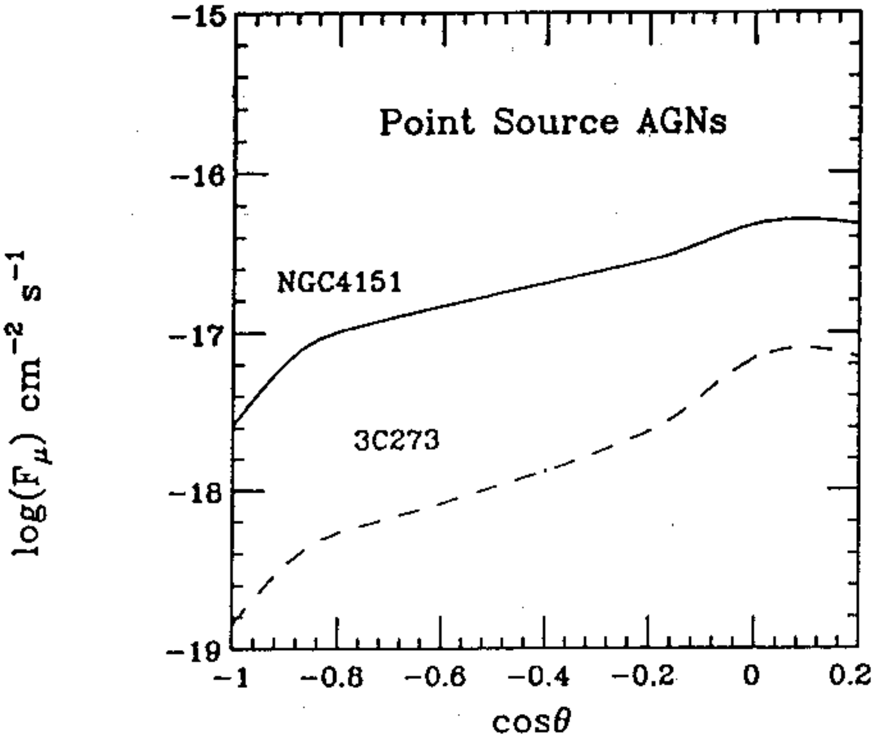

Fig. 3. Distributions in $\cos\theta$, where θ is the zenith angle of the muon, for neutrinos from two AGN point sources.

5. CONCLUSIONS

If the Stecker et al. predictions of the very high energy neutrino flux from active galaxies are correct within an order–of–magnitude, they should be detectable with DUMAND II. However only the net flux from all AGNs is significant. Point sources appear to be currently out of reach.

At the predicted rate, current experiments, in particular IMB and Kamiokande, might have been expected to see the first hints. Since neither positive nor negative reports from these experiments have appeared at this writing, I assume the question is still open. However, note that the flux does not exceed the atmospheric flux until one goes above about 300 GeV in muon energy. Thus experiments seeking this effect must make a high energy cut. DUMAND II will be able to do this, since it observes muons over a path length of 100 m or more and can estimate energy, at least crudely, from dE/dx.

The observation of AGN neutrinos would be remarkable in several respects. Not only would they provide a peek into the centers of the most energetic objects in the universe, but they would represent neutrino interactions at energies two orders of magnitude higher than those from earthbound accelerators. At these energies, the attenuation in the earth is substantial and this can be used to both study the very high energy νN cross section and do neutrino tomography of the earth.

This paper has focussed on the muons produced by ν_μ charged current interactions in the earth. As has been previously reported, the Glashow resonance can be searched for in the reaction $\bar{\nu}_e e^- \rightarrow W^- \rightarrow$hadronic cascade at 6.4 PeV, either via the Cherenkov light produced by the cascade or by an acoustic signal in he water.[6] DUMAND II will contain hydrophones in the array that will listen for messages of this nature.

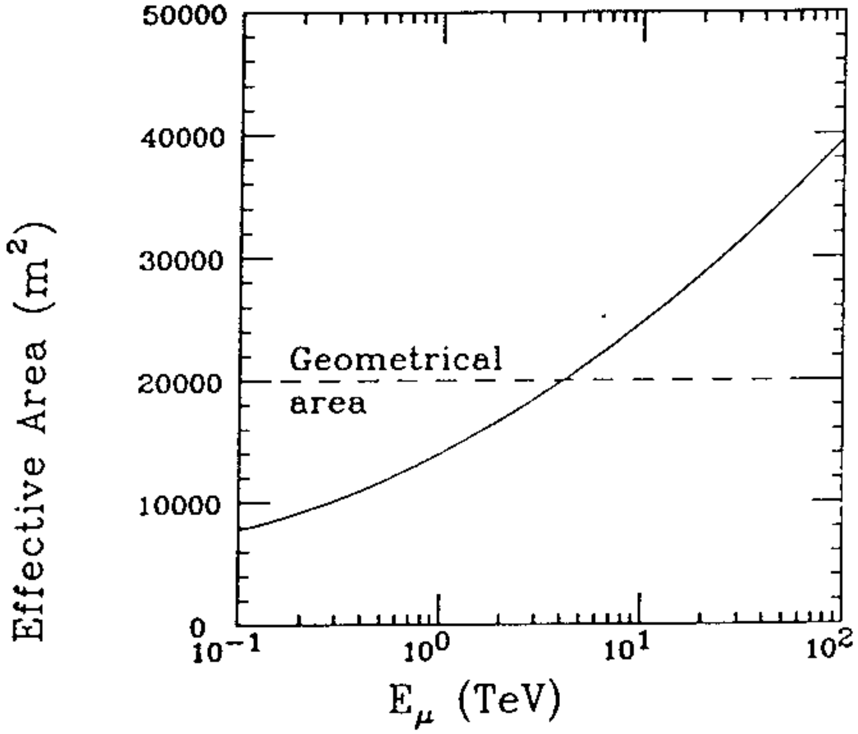

Fig. 4. The effective detection area of DUMAND as a function of muon energy. The geometrical area is 20,000 m^2.

6. REFERENCES

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