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LIMITS ON DEEPLY PENETRATING PARTICLES FROM THE FLY'S EYE DETECTOR

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Abstract

A search for deeply penetrating air showers, i.e. air showers which are initiated at depths $> 2000\text{g/cm}^2$ in the atmosphere, has been made using 0.64 years (live time) of Fly's Eye data. The absence of such events has placed limits on the flux of $> 10^{17}$ eV neutrinos which begin to encroach on proposed astrophysical production mechanisms.

Shower Trajectory Reconstruction: The Fly's Eye detector[1], which views the segmented 2π sr night sky with ~10^3 phototubes (each tube having a 5.5° aperture), determines the energies and trajectories of UHE ($> 10^{17}$ eV) cosmic rays by measuring the longitudinal profile of the primary's air shower in the atmosphere via the nitrogen fluorescence it generates. Figure 1 shows the track reconstruction geometry. The shower axis and the Fly's Eye determine a plane; phototubes illuminated by a shower form a great circle at the intersection of this plane with the detector's hemisphere. Since the phototube angular positions are fixed and well-known, the angle θ_n that the shower plane makes with the zenith has a relatively small measurement error; Monte Carlo studies show that the standard error varies from < 1° at $\theta_n = 20°$ to 2° at $\theta_n = 5°$. The trajectory of the shower *within* the shower plane is determined by fitting to the signal arrival times at each of the hit phototubes; from this fit the shower's zenith angle B_ is found. Timing errors are such that the location of the trajectory within the shower plane is less accurately known than the shower plane itself, resulting in zenith angle errors of ~ 5°-10°.

With θ_z measured, the longitudinal depth corresponding to maximum shower development[2], X_{max} which is a measure of the atmospheric penetration of the shower, is determined. Uncertainties in B.. can result in substantial errors in X_{max} and so only events seen in *stereo* by the neighboring FEI and FEII sites, where the trajectory is tightly constrained by the intersection of the two separate shower planes, are used to obtain an X_{max} distribution, shown in Figure 2[3]. These data were collected between 11/86 and 12/88; the dashed line represents the exponential fit to the tail of the distribution, corresponding to an effective proton-air mean free path ë = 70 ± 14g / cm^2. Note that X_{max} is tightly bounded from below by θ_n as seen by examination of Figure 1.

Deeply Penetrating Showers: We define a "deeply penetrating shower" as one whose X_{max} is so large that it is highly unlikely to have a proton progenitor. By scaling the distribution of Figure 2 to the total 1.65×10^5 reconstructed events in the Fly's Eye data set (spanning 2.03×10^7s of detector live time) the expected number of hadronic events with X_{max} X is tabulated below:

Expected Hadronic Events	X (g / cm^2)
10^0	1460
10^{-1}	1620
10^{-2}	1780
10^{-3}	1940
10^{-4}	2100

We have chosen to place our cut on X_{max} such that the a priori probability of contamination of our deeply penetrating sample by a proton is 10^{-3}, corresponding to $X_{max} > 1940\text{g/cm}^2$.

Because we wish to explore the entire FE data set, and not the restricted stereo subset, we cannot rely on Bz for this cut; instead, we place a cut 8„ _< 18°, which tightly constrains Xmax to be >_ 1940g/cm2. We find no deeply penetrating events satisfying this criterion. In addition, we have looked for events whose B„ are within 30 of our cut, and find none.

<u>Neutrinos:</u> The absence of deeply penetrating events at the Fly's Eye can place limits on the fluxes of any weakly interacting particles, such as neutrinos. Electron neutrinos through charged current interactions produce electrons carrying most of the initial lepton energy4, which then generate the observed electromagnetic shower. The expected number of neutrino events in our deeply penetrating sample is given by

$$N(E_1, E_2) = \tau \int_{E_1}^{E_2} \Omega(E) n(E) dE \qquad (1)$$

where ô is the detector live time (s), Ù(E) is the energy-dependent aperture (cm^2-sr). and n(E) is the differential neutrino flux. Ù(E) is determined by Monte Carlo, and is dependent upon the choice of neutrino-nucleon cross section ó$_v$n . We use the cross sections of Quigg et a1.[4], which include the effects of scaling violations at very high energy. The product ôÙ(E) (units of cm^2 - sr – s) *vs* energy E (units of GeV) is shown in Figure 3. (To use different cross sections, simply multiply the rS2(E) values of Figure 3 by the ratio of new cross section to the Quigg et al. cross section.) It, should be emphasized that without prior knowledge of the energy dependence of the neutrino flux, one cannot place upper limits on the neutrino flux as a function of energy. Only an upper limit to the normalization constant of an explicit, model-dependent n(E) can be found, given the result N(E^1, E^2) = 0.

Of the various models of production of cosmological, UHE neutrinos, two predict particularly high fluxes. In one[5], UHE cosmic ray proton production is assumed to track the integrated luminosity of active galactic nuclei, which increases as a power law in redshift[6]; thus the bulk of UHE protons are produced at high redshift. Since the microwave background temperature increases with redshift, photo-pion production of neutrinos[7] through pã Ä $^+$(1232) π^+n, followed by π^+ e$^+$v$_e$v$_ì$~~v~~$_ì$, results in a much larger flux than predicted by models without galactic evolution. In the second model[8], copious UHE neutrino production occurs at the cores of active galactic nuclei (AGN), again via photo-pion production through the Ä resonance, but in this model the interacting photons are not from the relic microwave background, but instead are optical photons from the AGN cores. In both cases, for the mast optimistic parameters, the predicted neutrino count from the Fly's Eye is of the order of 10^{-1}. Thus, to date, our limits on deeply penetrating events cannot constrain any present models of astrophysical production of UHE neutrinos. However, these results do indicate that a second generation detector, the High Resolution Eye[9], may very likely do so.

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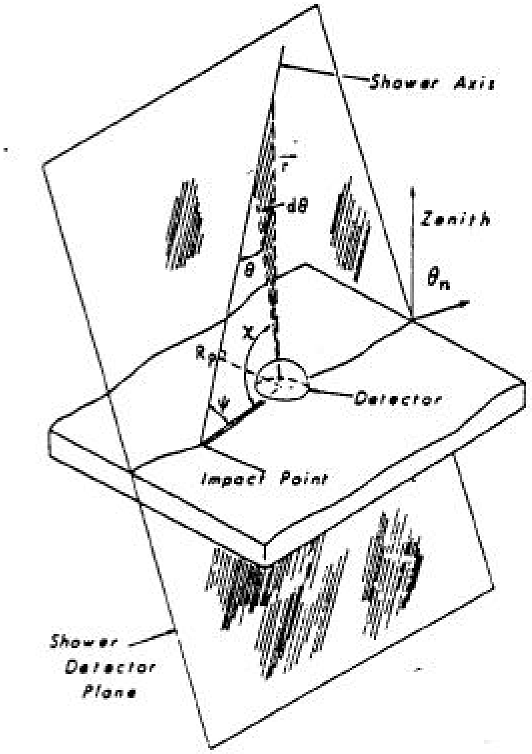

Figure 1

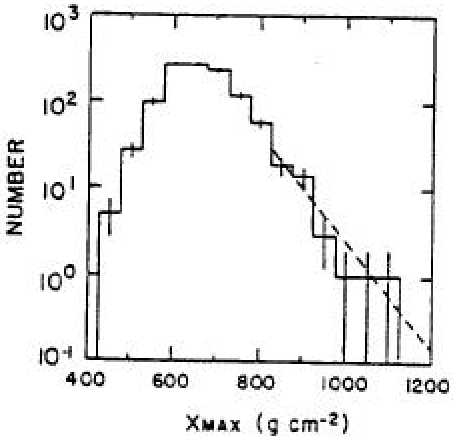

Figure 2

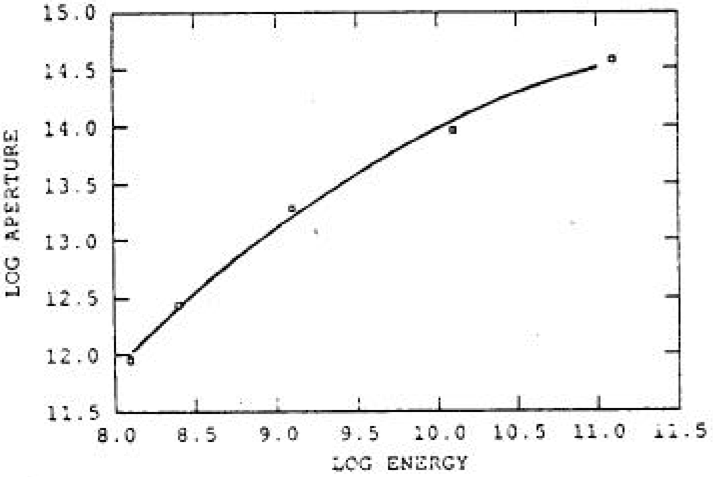

Figure 3