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Recent Results from the Utah-Michigan Extensive Air Shower Array

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Results from the Utah-Michigan extensive air shower array are presented. We describe the array and reconstruction techniques for air showers above 100 TeV and present preliminary results on a search for discrete and diffuse sources of UHE gamma rays, based on muon content. No excess long term activity is seen, with particular attention to Cygnus X-3 and the Crab nebula. Flux limits from Cyg X-3 are below recent reports, and no short term bursts from Her X-1 at the intensity of recent reports have been observed.

1. Introduction

The Utah-Michigan array is the first stage of the Utah-Michigan-Chicago extensive air shower experiment. It is located at the site of the Fly's Eye installation at Dugway, Utah ($40°N, 112°W, 860g/cm^2$). The present arrangement involves a surface scintillator array and a very large buried muon detector.

The combined surface and buried arrays are of sufficient size to enable detailed reconstruction of both the electromagnetic and muon component of extensive air showers with primary energies exceeding 100 TeV. Data taken from 29 March 1988 to 1 November 1988 have been analyzed for showers with a low muon count.

Gamma ray induced air showers are expected to have far fewer muons at the ground than showers of comparable energy initiated by primary protons and heavier nuclei. We will reject showers as being hadron initiated when the muon content exceeds one-tenth the expected mean number for showers of comparable electron size.

2. Apparatus

The surface array measures the electrons and photons of air showers. There are 33 stations, each with four plastic scintillators, arranged over an area of radius 100m (see Figure 1). An event is recorded when at least 7 stations and 15 counters report hits within 2 μsec. The time (to 2 nsec accuracy) and total pulse height are then digitized for each station.

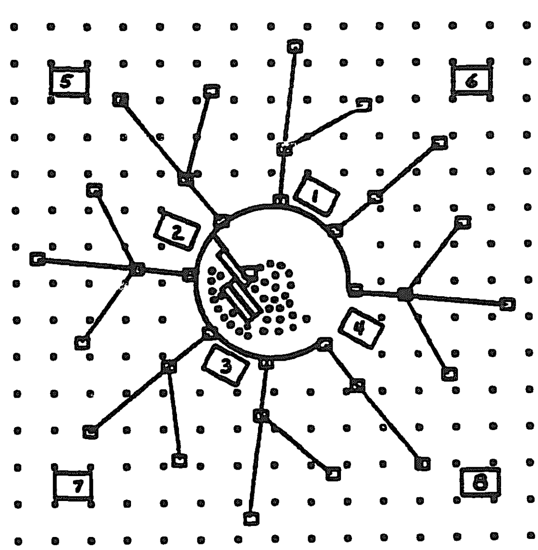

Figure 1. Layout of the Utah-Michigan array. The numbered rectangles indicate 64-counter muon banks. Grid marks are 15 m spacings; Fly's Eye II at center.

The muon counters are 2.5 m^2 rectangular plastic scintillators arranged in banks of 64 adjacent counters, buried at a depth of 3m; measurements and calculations indicate that electromagnetic punch-through is negligible at this depth. The times of all hits are digitized whenever the surface array reports a trigger.

The present configuration includes 8 banks, or 512 counters, and is the largest muon detector of any air shower array. The average triggered event records 35 muon hits along with 86 detected electrons. Ultimately the buried array will encompass 16 banks (1024 counters) and will operate with the large Chicago Air Shower Array (CASA)[1].

3. Reconstruction

Determination of shower parameters proceeds in several stages. The core of the shower is first approximated by averaging the locations of the surface array hits, weighted by the number of particles penetrating each. A direction is assigned by a least-square fit of the arrival times at each station to a plane wave front.

The lateral distribution of electrons and an improved core location are found by a least-square fit of surface counter data to an NKG function of fixed age. The direction of the shower is refined by fitting the arrival times to a cone-shaped front. The muon and electron lateral density functions are finally computed by separate maximum likelihood fits of surface data to an NKG function and muon counter hits to a Greisen muon density function. The total electron and muon sizes, N_e and N_μ, are determined by these fit normalizations.

The directional resolution is estimated by dividing the array in half, fitting each half separately, and comparing the results. We obtain resolutions from 3.0° to 0.7° for sizes from $N_e = 10^4$ to 10^6 respectively. Our absolute pointing accuracy is accurate to $< 0.3°$, as shown by comparison to independent fits of shower directions obtained by a tracking air-Cerenkov telescope operated in coincidence with the arrays.

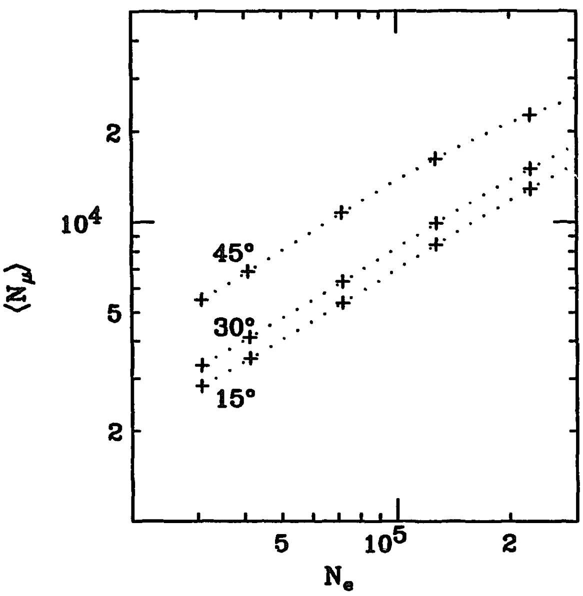

Figure 2. Mean muon size versus electron size for showers at various zenith angles.

The muon and electron sizes of showers are displayed in Figure 2. It is important to account for the zenith angle dependence of the relationship between N_e and N_μ since the electron and muon components of the shower develop differently as the shower progresses. We obtain

$$\log_{10}\langle N_\mu \rangle = -1.4 + 0.7\sec\theta + 0.9\log_{10} N_e.$$

The above coefficients above have mild dependence on atmospheric pressure so they are determined separately for each run (1 run $\sim$ 1 day).

4. Analysis for Muon-Poor Showers

The above relationship is used on a shower by shower basis to determine the relative muon content of each event. Figure 3 shows the distribution of relative muon size for showers with $N_e > 10^5$ and $> 3 \times 10^5$.

Monte-carlo studies of the muon and electron content of air showers indicate that cutting showers with less than one-tenth the expected mean number of muons will retain $\gtrsim 98\%$ of gamma ray induced events. Here and in what follows we will impose this condition to select gamma ray events or "muon-poor" showers.

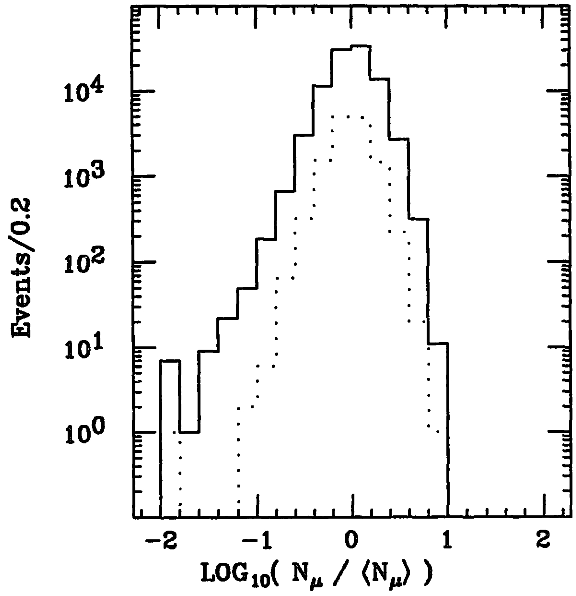

Figure 3. Distribution of relative muon sizes in a thirty day subset of data. Solid histogram is for $N_e > 10^5$, dotted for $N_e > 3 \times 10^5$.

Table 1 summarizes the results for showers of various sizes both over the whole sky and within 10° of the galactic plane. The "hadron rejection" factor is the fraction of showers observed with less than one-tenth the expected number of muons; The "γ fraction" is the 90% CL limit on the fraction of gamma induced showers in the total set, assuming all showers with $\log_{10}(N_\mu/\langle N_\mu \rangle) < -1$ are candidates.

Recent estimates suggest that gamma rays from primary cosmic ray protons interacting with interstellar material should be present at the 10^{-5} level. Figure 3 exhibits no clear enhancement of low muon showers but the muon-poor population is interestingly larger than might be expected by a simple extrapolation of the peak regions.

Table 1. Hadron Rejection

N_e	Hadron Rejection	γ fraction	γ fraction $\lvert b \rvert < 10°$
$> 1 \times 10^5$	1/1100	.0010	.0014
$> 3 \times 10^5$	1/4500	.0004	.0008

We have searched the northern sky in 5° bins for enhancements in the rate of showers. The background is estimated by distributing the entire data set, in local hour angle, over all right ascensions according to the measured sidereal time distribution. There are no statistically significant enhancements over background, either with or without muon cuts. Flux limits for declinations $20° to 60°$ are set at $> 3 \times 10^{-14}(7 \times 10^{-15}) cm^{-2} sec^{-1}$ for $E_\gamma > 3 \times 10^{14}(7 \times 10^{14})$ eV. We have looked at several regions in detail, described below.

5. Cygnus X-3

There have been many attempts to detect the x-ray binary system Cyg X-3 above 10^{14} eV since the reports by the Kiel group of excess air showers from this direction[2]. These observations and flux limits fall roughly along an integral spectrum extrapolated from x-ray and VHE data, parameterized as $4 \times 10^{-11} E_\gamma(TeV)^{-1} cm^{-2} sec^{-1}$.

The expected distribution of detected gamma ray events is determined for three data sets ($10^{4.5}, 10^{5.0}, 10^{5.5} < N_e < 10^{6.0}$). Our triggering efficiency is measured by measuring departures from the observed power law dN/dN_e spectrum. We convert N_e to primary gamma ray energy E_γ using monte-carlo results for the mean and dispersion in size. Folding this acceptance with the above gamma spectrum (modified to account for the expected absorption of the primary gamma ray beam on the 3°K microwave background) provides an expected spectrum of detected events.

Table 2 shows the observed and expected background events from within 3° of Cyg X-3, with and without cuts on the muon content. The quoted energy is the peak in the detected events distribution. We do not observe any significant excess in any case. 90% C.L. upper limits on the flux are obtained in the usual manner[3], assuming Poisson signal and background distributions.

Table 2. Cygnus X-3 Observations from 29 March to 1 November 1988

E(eV)	Observed Events	Expected Background	Flux(90%CL) ($cm^{-2}sec^{-1}$)
2.7×10^{14}	11240	11355	$< 1.4 \times 10^{-13}$
(μ-poor)	75	71	$< 2.1 \times 10^{-14}$
5.3×10^{14}	969	1004	$< 5.6 \times 10^{-14}$
(μ-poor)	2	1.2	$< 6.6 \times 10^{-15}$
1.5×10^{15}	82	99	$< 2.4 \times 10^{-14}$
(μ-poor)	0	0.05	$< 5.6 \times 10^{-15}$

Use of the muon-poor criteria greatly reduces the data set and permits flux limits to be set a factor ~ 3 below the spectrum suggested by earlier reports (see Figure 4).

It is worth noting that while it is necessary to assume a spectral index to obtain the energy corresponding to the N_e cuts, the flux limits do not depend on this assumption.

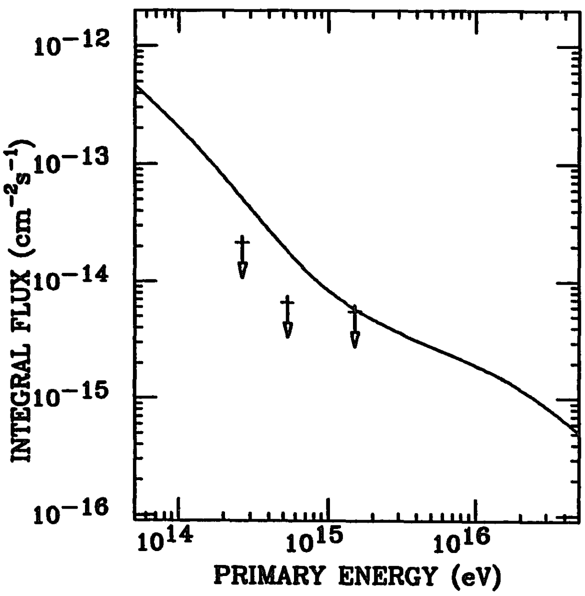

Figure 4. Upper limits (90% CL) on steady flux from Cyg X-3 using muon-poor showers. Solid line is a fit to lower energy data adjusted for gamma-ray absorption on 3°K photons in 10 kpc.

6. Crab Nebula

We have performed a similar analysis on data from the direction of the Crab Nebula. The Crab has been repeatedly seen to emit steady VHE radiation with characteristics expected of gamma rays; the integral spectrum, taken from the recent observations from the Whipple[4] and γ^{+}[5] experiments as well as x-ray results, is apparently much steeper than Cyg X-3, falling roughly as $E^{-1.7}$. The expected rate of UHE events is then much smaller than that expected from Cyg X-3.

Table 3 shows the observed and expected rate of events from the Crab. There is no unusual excess from this object and flux limits are obtained as before. These limits are roughly a factor of twenty higher than the extrapolated flux mentioned above.

Table 3. Crab Nebula Observations from
29 March to 1 November 1988

E(eV)	Observed Events	Expected Background	Flux(90%CL) ($cm^{-2}sec^{-1}$)
3.4×10^{14}	6618	6537	$< 2.8 \times 10^{-13}$
(μ-poor)	33	42	$< 1.0 \times 10^{-14}$
7.5×10^{14}	559	572	$< 4.6 \times 10^{-14}$
(μ-poor)	1	0.8	$< 4.6 \times 10^{-15}$
1.7×10^{15}	50	55	$< 2.1 \times 10^{-14}$
(μ-poor)	0	0.03	$< 4.4 \times 10^{-15}$

7. Hercules X-1

We have made a preliminary search of our data for bursts of events from Her X-1 and tested for periodicity at or near the x-ray period. This analysis is prompted by the recent reports from the CYGNUS experiment at Los Alamos of the observation of two 30 minute bursts of air showers at an anomalous period[6]. Since this observation suggested the signal was not muon-poor, the analysis did not require such criteria, *a priori.*

The event rate was monitored for data taken from 29 March 1988 to 12 October 1988 (197 days) in a sliding 45 minute time window. Fourteen runs were found with episodes of excess rate having less than 1% probability of being an upward fluctuation of the measured average rate. The most improbable run showed excess activity from the direction of Her X-1 about 3σ above the expected background. When a muon-poor cut is applied, no run showed any excess from the source.

Data in the most unlikely run were searched for periodicity from 1.226 sec to 1.246 sec using the Protheroe test; there was no evidence for any unusual activity. We then searched all runs with more than 10 events from the direction of Her X-1 in the same period window and again found no unusual period peaks.

The mean energy of this analysis is roughly 500 TeV, somewhat higher than the Los Alamos report; the flux sensitivity is approximately $3 \times 10^{-11} cm^{-2} sec^{-1}$. We conclude that we have observed no episodes of emission from Her X-1 during this period similar to that reported by the CYGNUS experiment.

8. Summary and Outlook

The large muon array operating with the present surface array allows substantial rejection of hadron primaries. Limits on the fraction of gamma rays in the primary cosmic-ray flux approach levels where products of EeV protons interacting on interstellar material will become observable (10^{-5}). Hadron rejection presently permits a sensitivity to steady emission from Cyg X-3 at a level better than previous reports; further improvement is necessary in order to observe the Crab nebula above 100 TeV. We anticipate the improved angular resolution and large size of the CASA array, wnen in operation with the muon detectors, will provide the enhancements necessary to observe such effects.

References

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6. B. L. Dingus, et al., *Phys. Rev. Lett.* **61**, 1906 (1988).