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Title: The Status of the CYGNUS Experiment: Past, Present, and Future

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The Status of the CYGNUS Experiment: Past, Present, and Future

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The CYGNUS experiment, located in Los Alamos, NM, has been continuously operating since April 2, 1986. The experiment consists of an air shower array and an associated 44 m^2 muon detector; its large size, good angular resolution, muon detection, and low energy threshold make it a unique experiment among those currently operating. The experiment has undergone continuous expansion in several stages since it began operation. The experiment, its expansion, and further plans for the future will be described.

1 Introduction

The field of high-energy astrophysics has seen rapid expansion in the last several years. This is partially due to recent observations of several point sources at both VHE ($\sim$ 1 TeV) and UHE ($\sim$ 100 TeV) energies. Perhaps the most striking result was the observation of muon-rich air showers from the direction of Cygnus X-3[1]. It was in this climate of unexpected results in the UHE energy regime that the CYGNUS experiment was begun.

There are several characteristics that any air-shower experiment should have to be able to search for point sources. These include good angular resolution for source identification and background supression, reliable muon identification to eliminate the possibilities of non-muonic contamination, and low energy-threshold and large area to provide both good counting statistics and short-term burst sensitivity. As described below, the CYGNUS experiment meets all of these needs and on-going expansion will continue to increase the capabilities of the experiment; the long-term goal of performing high duty factor VHE observations will also be described. Recent results on Cygnus X-3,[2] Hercules X-1,[3] and other interesting physics[4], can be found in the literature.

2 The Past: The CYGNUS-I Array

The CYGNUS air-shower array[5] is an array of scintillation detectors deployed around the end of the LAMPF accelerator, to make use of an existing neutrino detector, at Los Alamos National Laboratory in Los Alamos, NM. It is located at 35.9°N latitude, 106.7°W longitude, and an altitude of about 2,100 m (7,000') corresponding to an atmospheric overburden of about 800 g/cm^2. The CYGNUS-I array currently consists of a total of 108 counters spread over an area of about 20,000 m^2.

Each scintillation detector, shown schematically in Figure 1, has a single 2" photomultiplier tube in a light-tight fiberglass enclosure viewing a scintillator of area 0.83 m^2. The information recorded for each event includes the relative time each detector was hit (with a signal corresponding to at least about 0.1 minimum ionising particle) as well as the relative pulse height of the signal. The detectors are regularly calibrated using single penetrating particles recorded in coincidence with a separate pair of smaller counters placed in turn directly under each detector.

The location of the experiment at an existing facility dedicated to physics research has made operation and maintenance of the experiment in many respects simpler. Placement of the array around the beam stop results in a rather irregular pattern, shown in Figure 2, with some detectors located on buildings or hillsides, but this pattern does not effect the overall performance of the array; the reason for

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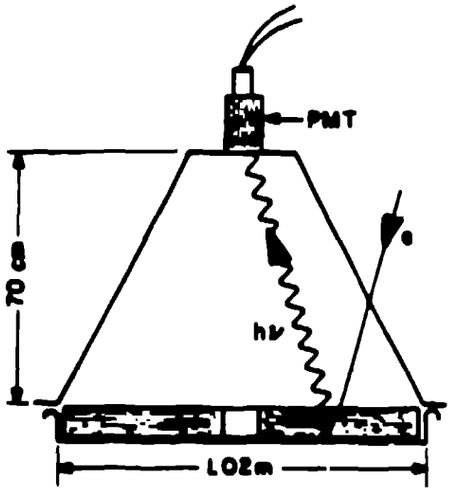

Figure 1. Schematic of PMT and scintillator in light-tight enclosure. The height of the enclosure reduces path-length differences between the scintillator and the PMT.

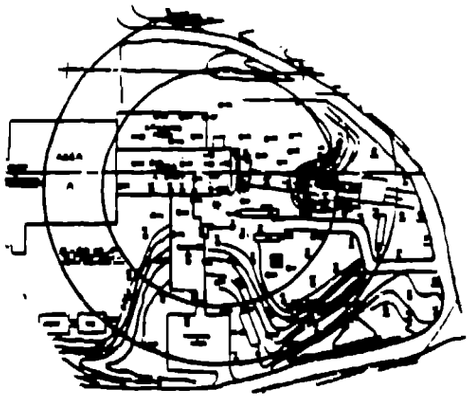

Figure 2. Deployment of the counters around the LAMPF beam stop. Each circle represents a counter. Buildings, roads, etc. are also shown. The * represents the approximate location of the E225 detector.

the irregular pattern is the many buildings, trailers, roads, and parking lots in the area. Deployment of the array was accomplished in three stages; the array began taking data on April 2, 1986 with a total of about 60 counters, with 4 more added soon after, spread over about 10,000 m^2. An additional 32 counters were added in July, 1987 increasing the area covered to about 20,000 m^2. Finally, 12 counters were added in December, 1988 to fill in the remaining area to the east near the eventual location of the CYGNUS-II array. The spacing between counters ranges from about 10 m in the central part of the array to about 20 m near the edges, especially towards the east, with an average of about 14 m between counters.

A layer of lead, approximately 1 radiation-length thick, has been recently placed on (nearly) all of the detectors. The lead has resulted in slight improvements in energy threshold and angular resolution; determination of the quantitative of improvement of energy threshold, effective area, and angular resolution is difficult, requiring many detailed studies of the data; the results will be forthcoming.

All of the signals from the counters are brought to a single, centrally located trailer for triggering, digitization, and read out. The array is triggered, at a rate of about 3.2 s^{-1}, by at least 20 counters in coincidence. An additional requirement of at least 8 counters being struck by at least 2 particles each, which about 70% of the events meet, is made before the event is recorded to tape for later reconstruction and analysis.

The zenith angle distribution of recorded events, averaged over about a day of running, is peaked within 1° of the zenith and varies approximately as $\cos^7\theta_z$. The distribution is not peaked exactly at the zenith because of the irregular deployment of the detectors, mostly due to the relative height variation of about 15 m. The angular resolution, as a function of the number of detectors used in reconstruction, is shown in Figure 3; the median number of detectors used in the fit is about 20 resulting in an average resolution of about 0.8°. The primary energy distribution of cosmic ray showers is shown in Figure 4. The decrease at low energies is due to trigger losses and at high energies it is due to the decreasing cosmic ray spectrum. The typical energy of cosmic ray events is about 200 TeV and the array threshold is about 50 TeV.

3 Muon Identification in CYGNUS-I

The CYGNUS-I array is deployed around the LAMPF E225 neutrino-electron elastic scattering experiment, the first experiment to observe $\nu_e - e$ scattering[6], shown in Figure 5. The E225 detector is shielded on the top by 1.8 m iron equivalent and on three of the four sides by 1.0 m iron equivalent (the fourth side, toward the beam stop, is shielded much more). This shielding corresponds to about 50 radiation lengths and about 12 nuclear-interaction lengths for the top (30 radiation lengths and 7 interaction lengths for the sides). The minimum energy required for a vertical muon to pen-

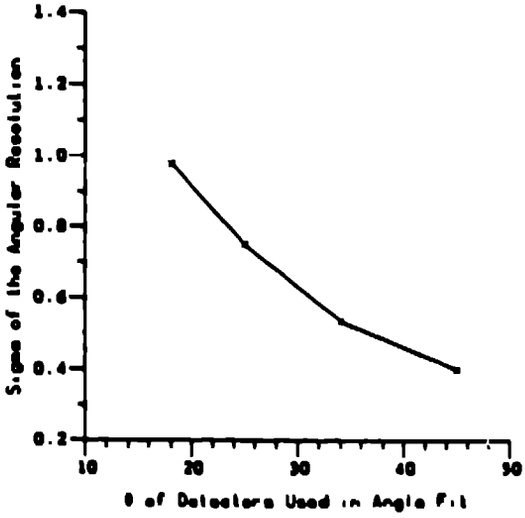

Figure 3. Angular resolution of the CYGNUS-I array as a function of the number of detectors used in reconstruction. The main requirement is that a detector must have a signal of at least 1 equivalent minimum ionising particle.

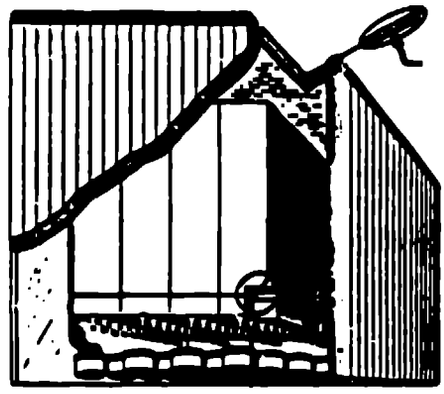

Figure 5. Schematic representation of the E225 neutrino detector showing both the inner detector and the MWPC anticoincidence detector.

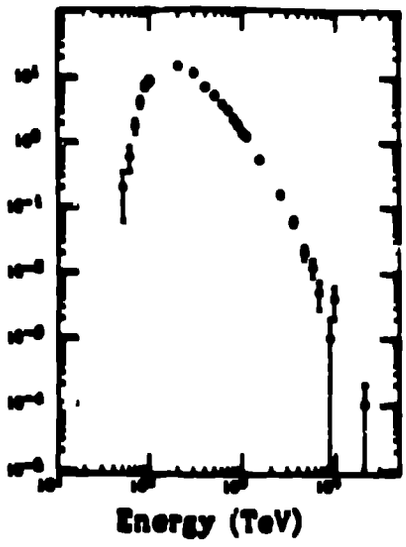

Figure 4. Primary energy distribution of events detected in the CYGNUS-I array.

etrate the top shield is 2.5 GeV while for a muon entering the side at a 45°zenith angle it is 2.0 GeV.

Inside the shielding the multiwire proportional chamber detector used as an anticoincidence veto for the neutrino experiment serving as the muon detector for the CYGNUS experiment. This detector, with an efficiency greater than 99%, is a cube 6 m on a side resulting in a minimum area of 36 m^2 of muon detector; the total projected area of the detector for a typical shower is 44 m^2.

A fine-grained neutrino detector was installed inside the shielding/veto system. Reconstruction of muons passing through this detector can be used to compare the muon direction with the reconstructed air-shower direction to search for systematic angular errors in reconstruction. Muon multiple scattering in the shield is expected to be about 1°. Figure 6 shows the angular difference distribution, in right ascension and declination, for a sample of such events. Clearly, there is no evidence for systematic reconstruction errors in this data greater than 0.2°. The centeral detector met its eventual demise as the need for scintillator arose for deployment in the CYGNUS-II array and its muon detector.

4 The Present: The CYGNUS-II Array

The energy of events detected in a burst from Hercules X-1 in 1986 by the CYGNUS experiment[3] was clearly different

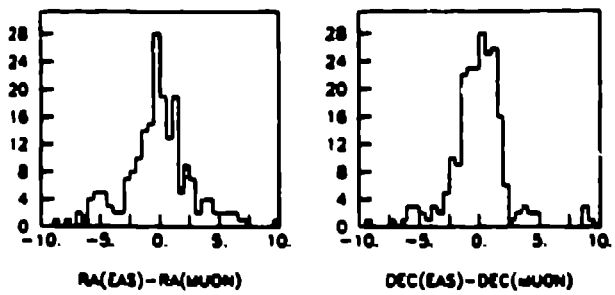

Figure 6. Angular difference, in right ascension and declination, between the reconstructed air-shower direction and muon direction.

than the background distribution. There is therefore a clear indication that the spectrum of the burst events is harder than the cosmic-ray background; thus, a large air-shower array designed to concentrate on higher energies will optimize the observed signal and at the same time minimize the number of detectors required to cover a given area. This was the goal of the current expansion effort, known as CYGNUS-II, which is designed to greatly expand the area covered by the CYGNUS experiment.

The CYGNUS-II array is made up of 96 counters, nearly identical to the CYGNUS-I counters except for their area, 1.0 m^2, deployed over an area of about 60,000 m^2. The counters are arranged logically into 6 distinct "subarrays" of 16 counters each, as shown in Figure 7; the reason for this is to help reduce the electronic gate widths required for an array of such size. The spacing between counters varies from 20 m for the two subarrays nearest CYGNUS-I to 30 m for the two furthest from CYGNUS-I. The reason for the graded approach is to expand the high-energy capabilities of the CYGNUS experiment in a smooth fashion.

The electronics for CYGNUS-II are somewhat different than those in CYGNUS-I and are located in a trailer centrally located within the CYGNUS-II array. This eliminates the unacceptably long cable lengths that would be required to reach the CYGNUS-I electronics trailer. Timing and pulse height measurements are still made for each counter but, instead of a single global trigger for the entire array, each subarray has its own lower-level local trig-

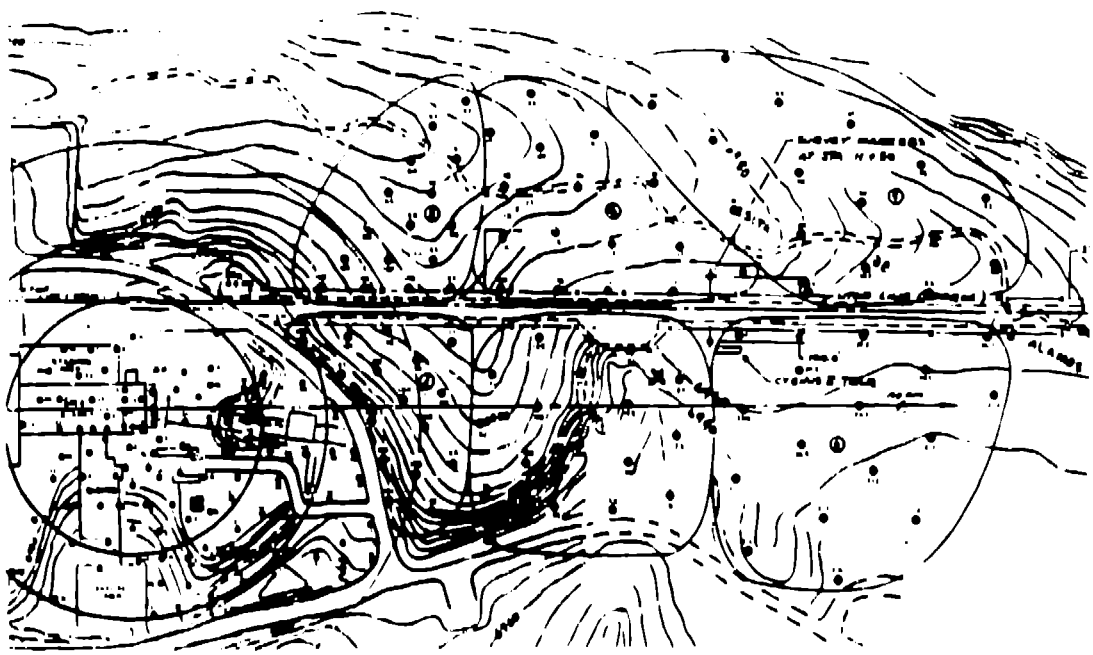

Figure 7. Deployment of the CYGNUS-II array showing the grouping into six subarrays. The * here represents the approximate location of the anasazi muon counters.

ger; a global trigger can be generated either by the requirement that at least some minimum multiplicity of counters in CYGNUS-II is met or by a trigger from CYGNUS-I (and vice versa). The array is controlled by the computer which operates CYGNUS-I . It is thus possible to have both arrays act as if they were simply a single, very large array without unacceptably long cable runs.

A relative comparison of the capabilities of CYGNUS-I and the combination of CYGNUS-I and CYGNUS-II can be made by calculating the integral effective area, assuming a source integral power-law spectrum with spectral index $\gamma = -1.0$, below an energy E, all normalised to the integral effective area of the original CYGNUS-I array with 64 detectors. The comparison is then the ratio of the number of detected events from a source with such a spectrum; the results are shown in Figure 8. The comparison for several energies is

E (TeV)	$\frac{\text{CYG-I}_{96}}{\text{CYG-I}_{64}}$	$\frac{\text{CYG-II}}{\text{CYG-I}_{64}}$
10^{14}	1.6	2.5
10^{15}	1.6	3.2
10^{16}	1.6	3.3
10^{17}	1.6	3.8

where the two columns represent a comparison of CYGNUS-I with 96 counters (and the combination of CYGNUS-I and CYGNUS-II) with CYGNUS-I with 64 counters, respectively.

Deployment of the counters is underway and they should become entirely operational by the end of 1989.

5 Muon Identification in CYGNUS-II

Several options for muon detection in CYGNUS-II were considered from shielded fine-grain detectors to buried scintillator. When the option of buried scintillator was chosen, an obvious site presented itself. In nearly the exact center of the CYGNUS-II array there is an arroyo at least 30 feet deep. Since the local rock is soft, it is easy to manipulate; thus, the idea of simply drilling holes in the side of the arroyo and installing scintillator counters, taken from E225, was pursued. The muon detector for CYGNUS-II is known as "Anasazi", after the cliff-dwelling indians who inhabited the area about 1000 years ago.

There are a total of 15 holes, each 36 in. in diameter and 40 feet deep, shown schematically in Figure 9. Two scintillation counters, each 30 in. wide and 10 feet long (area 2.3 m^2), will be placed in each hole; the total area for the 30 detectors is 70 m^2. The holes are covered by at least 18 feet (5.45 m) of rock, of density 1.3 g/cm^3, corresponding to a minimum overburden of 710 g/cm^3.

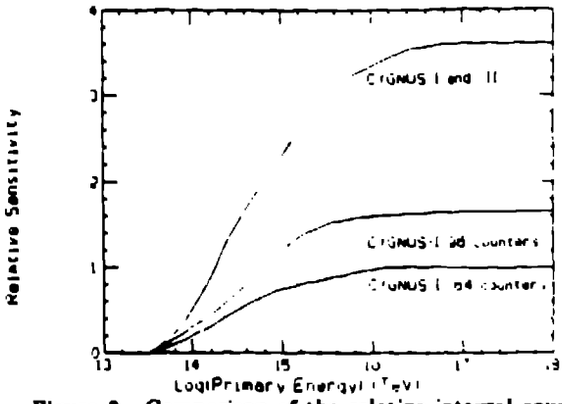

Figure 8. Comparison of the relative integral counting rate, as a function of energy, for the full CYGNUS-I array and the combination of CYGNUS-I and CYGNUS-II arrays.

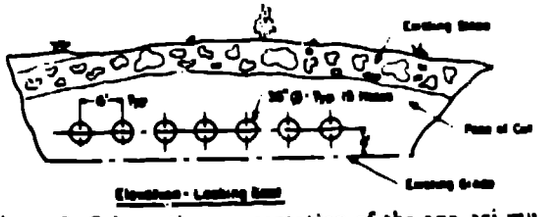

Figure 9. Schematic representation of the anasazi muon counters.

6 The Future: The CYGNUS-III Array

There are several possible options which could be the next step for the CYGNUS experiment. For example, continued expansion to larger area, continued deployment over the present area for lower energies, and more or better muon detection. All of these options would be a continuation of more detailed studies of the same phenomenon. Instead, the CYGNUS collaboration has chosen to pursue an entirely different goal, that of performing high-duty factor observations in the VHE domain. The motivation for this is several fold: there seem to be more sources observed at VHE energies, the known sources seem to burst more often, it is likely that there are undiscovered sources at these energies, and there is a largely unexplored region in energy from the ~ 1 TeV region where air-Čerenkov telescopes operate to the ~ 100 TeV region of EAS arrays. The goals for this new effort strongly suggest a solution based on the EAS array concept. Whatever the solution, an extensive muon detector will be required if it is desired to search for muons in showers at these energies.

The most obvious solution would be deployment of standard scintillator counters in a very dense array, tentatively known as "dense pack." Such an air-shower array, with scintillator covering about 10% of the total area (0.5% is now typical) of about 10,000 m^2, could observe showers from primary energies as low as 1 TeV with the typical energy

of about 5 TeV. The energy-dependent angular resolution would vary from about 2° at threshold to 0.7° at 20 TeV. Such a detector, as a simple extension of decades old techniques, could be easily built and would cost several million dollars. Another option, based on the water-Čerenkov technique, is also being explored.

7 Conclusion

The CYGNUS experiment has been operating continuously since April, 1986. The current expansion effort will increase the sensitivity of the array a factor of about three with increased focus on higher energies. The next step will be an attempt to design and build a detector capable of observing energies in the unexplored region between 1 TeV and 100 TeV with high-duty factor. With continued effort, the CYGNUS experiment will continue to be a unique resource at the forefront of the field making observations which should help expand our understanding of the physics, both astrophysics and particle physics, operating at multi-TeV energies.

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