SCIPP 92/39
September, 1992

RECENT RESULTS FROM THE CYGNUS EXPERIMENT AND PLANS FOR THE MILAGRO EXPERIMENT

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Representing the CYGNUS* and MILAGRO† Collaborations

Abstract

Recent results from the CYGNUS cosmic-ray experiment are presented, including a survey of the northern sky for continuous point sources and a search for emission lasting several hours (one day of observation) from many known x-ray and γ-ray sources. The performance of five water-Čerenkov detectors recently added to the CYGNUS array is summarized. A proposed water-Čerenkov detector called MILAGRO for the detection of cosmic-ray air showers over a broad energy range, 1–1000 TeV, is described.

The CYGNUS extensive air-shower experiment began operation in April 1986 with 50 scintillation counters, located around the Los Alamos Meson Physics Facility beam stop (106.3°W, 35.9°N). One of its primary goals is the search for point sources of cosmic rays. The array has been expanded substantially since 1986. This paper describes data taken with the CYGNUS-I array, which presently has 108 counters, including the original 50, covering an area of 22,000 m^2. The median primary energy for detected gamma-ray initiated events is about 80 TeV in the present configuration; for protons, the median is about 100 TeV. Studies of the cosmic-ray shadows of the sun and the moon[1,2] have shown that the CYGNUS array has a resolution for the projected angle of $0.66° \pm 0.07°$. The CYGNUS-I event rate is presently about 3.5 events/s. A more detailed description of the the CYGNUS experiment can be found elsewhere.[3]

The MILAGRO collaboration, an outgrowth of the CYGNUS group, has recently proposed a new experiment to measure air showers using a large water-Čerenkov detector. The water-Čerenkov technique shows great promise for providing air-shower detectors with large sensitive area at low cost. To enhance the CYGNUS experiment, as well as to investigate the water-Čerenkov method in detail, five 42 m^2 water-Čerenkov detectors have been added to the CYGNUS array.

The remainder of this paper is divided into three sections. The first section discusses results from the CYGNUS experiment. The middle section describes the performance of the five CYGNUS water-Čerenkov detectors. The final section contains a description of the proposed MILAGRO experiment.

CYGNUS RESULTS

The CYGNUS data set from April 1986, to May 1991, has been used to search declinations

Invited Talk, XXVI International Conference on High Energy Physics, Dallas, Texas, August 6–12, 1992.

from 0° to 80° for continuously emitting point sources.[4] For this survey, the northern sky is divided into 14,400 overlapping bins approximately 2.4° on a side. (3600 nonoverlapping bins are required to cover the region.) For each bin, the number of events is compared to the number of expected background events. The expected background is calculated from the data by randomly associating the time of each event with the direction of other events, as described in Ref. 4. The differences between the observed and expected number of events in each bin are all compatible with statistical fluctuations of the background: we do not find evidence for emission from a source.

In addition to the set of bins covering the sky, we have examined bins centered an several candidate sources. Again, no evidence for emission is observed. Flux upper limits (90% confidence level) for four of the sources are given in Table 1. A complete list of the sources studied is given in Ref. 4.

Recently, the EGRET experiment[5] on the Compton Observatory and the Whipple experiment[6] have detected gamma rays from the distant active galactic nucleus Markarian 421. These measurements indicate a differential energy spectrum of roughly E^{-2} from this object. Because of its distance (about 4×10^{24} m), photons with energy above about 100 TeV are expected to be absorbed by e^+e^- pair production off the 2.7 K microwave background.[7] We have made a preliminary calculation of our sensitivity to a source at the declination of Mkn 421 with an E^{-2} spectrum, cut off by the effect of the microwave background.[‡] Using our data from April 1986, through June 1992, we obtain a preliminary upper limit for the flux from Mkn 421 above 60 TeV of 1.3×10^{-13} cm^{-2} s^{-1} (90% c.l.).

We have also conducted a search for emis-

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‡Some authors (see Ref. 8) have argued that the field of infrared radiation is sufficient to produce significant absorption at energies above about 1 TeV. Because of the uncertainties in the amount of infrared radiation present, we have not attempted to take it into account.

Table 1. Flux limits for continuous emission from some candidate sources.

Source	Flux upper limit above 40 TeV
Crab	$< 4.4 \times 10^{-13}$ cm^{-2} s^{-1}
Cyg X-3	$< 1.9 \times 10^{-13}$ cm^{-2} s^{-1}
Geminga	$< 4.1 \times 10^{-13}$ cm^{-2} s^{-1}
Her X-1	$< 1.6 \times 10^{-13}$ cm^{-2} s^{-1}

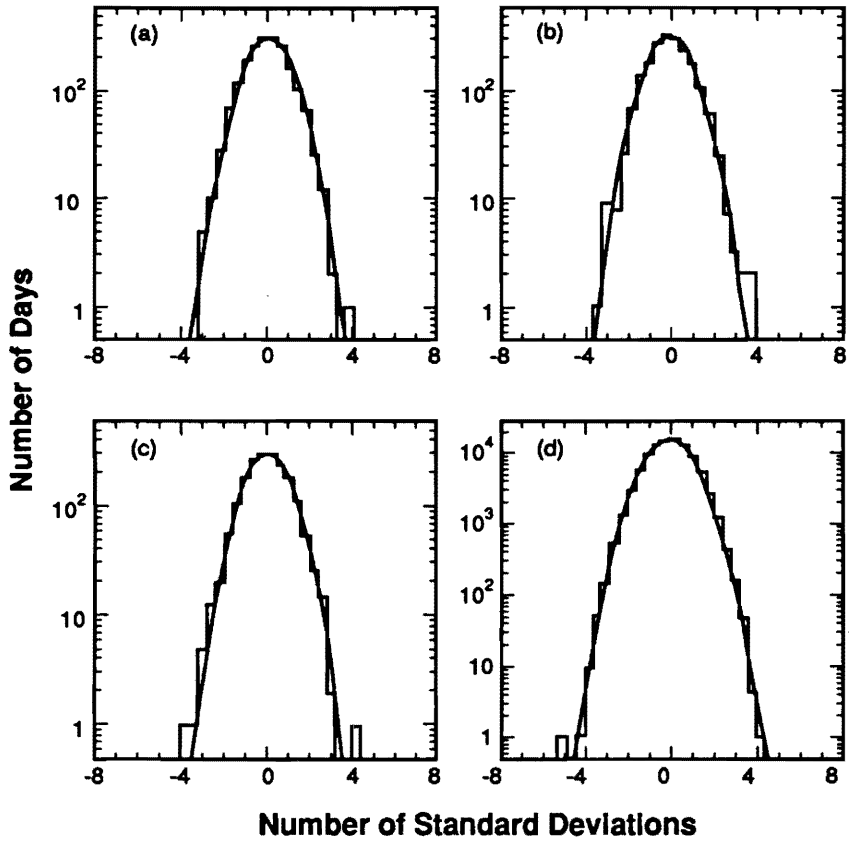

Figure 1. Distribution of daily excesses from (a) Cyg X-3, (b) Her X-1, (c) the Crab, and (d) an ensemble of 48 other objects. Superimposed on each of the four histograms is the best fit to a Gaussian distribution.

sion lasting about one day of observation from many candidate sources.[2] We compare the number of observed events to the expected number of background events, calculated on a day-by-day basis. The excesses, in terms of standard deviations, are shown in Figure 1. There is no evidence for any excess beyond what is expected from statistical fluctuations.[§] Typical flux upper limits are given in Ref. 2. They are generally of order 10^{-12} cm^{-2} s^{-1}.

THE CYGNUS WATER ČERENKOV DETECTORS

The water-Čerenkov detection technique offers an inexpensive way to achieve large active areas, thus measuring more of the shower particles, including photons. Numerous measurements of the arrival time of the shower front made possible by this technique yield excellent angular resolution. The denser sampling of the shower can also result in a much lower energy threshold than a conventional scintillator array, as in the case of MILAGRO.

Five water-Čerenkov detectors, constructed from commercial swimming pools fitted with light-tight covers, have been installed in the CYGNUS array. The first of these pools was constructed in the center of the array and verified many details of the simulations used to develop the MILAGRO proposal.[12] The results also indicated that the addition of several more pools to the CYGNUS array could substantially improve the angular resolution,

[§]Note that the 1986 Hercules burst previously published (Ref. 11) is significant primarily because of the observed periodicity in addition to the excess of events.

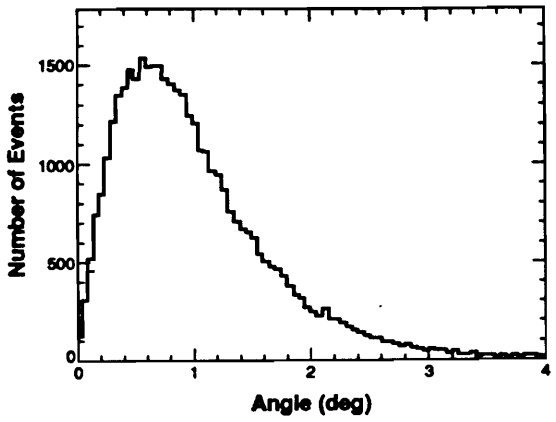

Figure 2. Space angle difference between air showers reconstructed with the CYGNUS scintillation counters and the five pools.

motivating the installation of four more pools.

All five pools are now in operation. They are read out with each CYGNUS trigger. Each pool is equiped with seven Burle C83061E photomultiplier tubes. Figure 2 shows the space angle difference between the shower direction reconstructed with the CYGNUS scintillation counters alone and the direction reconstructed with the water-Čerenkov detectors alone. Events in this distribution have at least 15 tubes fired in at least four pools; 75% of the events meet this criterion. The standard deviation deduced from this distribution, 0.74°, together with the resolution of 0.66° for the scintillators alone, implies an angular resolution for the pools of about 0.3°. This agrees with the predictions of Monte Carlo simulations. An analysis using the pools of the cosmic-ray shadows of the sun and moon is in progress.

MILAGRO

MILAGRO takes the water-Čerenkov technique one step further, using a large water reservoir as the main component of the detector. It is designed to observe cosmic gamma rays over a broad energy range of 1 TeV to 1000 TeV. The air-Čerenkov technique is sensitive to air showers produced by primary cosmic rays at the lower end of this energy range, about 1 TeV, while widely-spaced detector arrays are sensitive to showers from primaries above about 50 TeV. The MILAGRO detector will be sensitive to cosmic-ray showers in both of these energy regimes, but will also be the first detector for studying events in the entire energy interval between these two regions.

The experimental site (106.7° W, 35.9° N) is about 55 km west of Los Alamos, New Mexico, at an elevation of 2650 m. The design of MILAGRO makes use of an existing water reservoir, which is 8 m deep and has surface dimensions of 60 m by 80 m. The walls of the reservoir are slanted such that the bottom has about a third as much area as the surface.

MILAGRO requires photomultiplier tubes (PMTs) with at least 8″ photocathode diameter, excellent timing resolution, and good charge resolution. The PMTs will be deployed in two layers in the pond, which will be filled with purified water. The first layer of 408 tubes, viewing the meter of water below the surface of the pond, will be used to measure the time of arrival of an air-shower wave front as it produces Čerenkov light in the water. A second group of 170 tubes will be optically isolated at about 7 m depth, viewing a 1 m thick layer of water covering the 1500 m^2 area at the bottom of the pond. This layer will be sensitive to muons, allowing us to study the muon content of showers. The pond portion of the detector will be surrounded by 204 scintillator detectors from the CYGNUS experiment, increasing the physical area to about 40,000 m^2.

MILAGRO would be the first experiment to observe the entire overhead sky 24 hours a day at energies near 1 TeV. Air-Čerenkov experiments, which are responsible for our present knowledge at 1 TeV, are only able to observe

one source at a time and only on clear, dark (little or no moonlight) nights. Two other attractive features of MILAGRO are a high-altitude location, where for a given air shower the number of detected particles is greater than at sea level, and a modest cost of about $3 million.

The response of the proposed detector to incident showers initiated by photons and hadrons has been studied using Monte Carlo simulations. The shower from a 2 TeV primary gamma ray contains on the average only 250 electrons incident on the pond. A conventional scintillator air-shower detector such as the CYGNUS array would detect about one of these electrons. On the other hand, MILAGRO will detect on average about 1150 photoelectrons, providing ample information on the shower front. We have studied the detector trigger efficiency, angular resolution, and muon detection efficiency.

Air-shower arrays do not have a sharp energy threshold. The proposed trigger requirement for MILAGRO is 50 struck PMTs, each recording at least one photoelectron. From the Monte Carlo simulations, this results in a total cosmic-ray trigger rate of about 1200/sec and an energy distribution for triggered events that peaks below 1 TeV.

The resolution in arrival direction measurement is a critical feature of the apparatus, because the signal-to-noise ratio in a point source search varies inversely as the square of the angular resolution. For PMTs located 20 m from the core and 1 m below the surface of the water, the arrival time distribution of the first Čerenkov photon has a width of 1.1 ns rms. This value is comparable to that obtained at the same core distance from the electrons in the incident shower, indicating that for shallow PMT depths, the Čerenkov light propagation time does not degrade the time resolution.

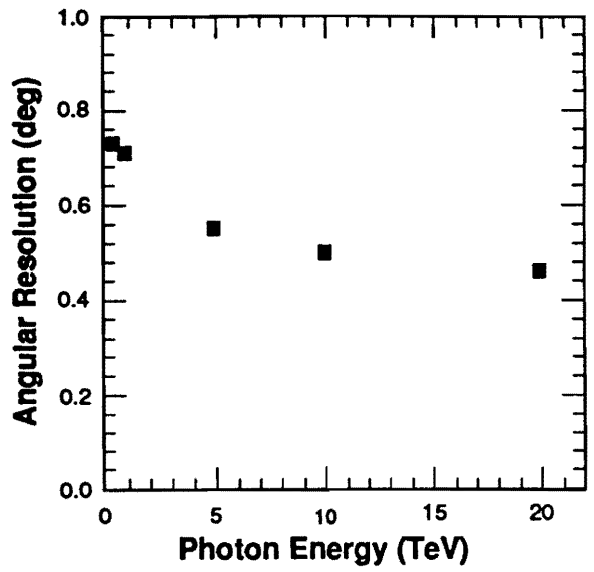

Figure 3. Angular resolution of the MILAGRO detector for photon-initiated showers.

These simulations yield an angular resolution for MILAGRO well under a degree, as shown in Figure 3.

A vertical muon of energy greater than 1.75 GeV will penetrate to the bottom of the MILAGRO pond, with an average of 20 photoelectrons detected in the muon layer. This ensures a high efficiency for muon detection.

The Monte Carlo simulations of cosmic-ray showers have been used to determine the probability that one or more muons are detected in a hadron-initiated shower. Near 1 TeV about 25% of hadron showers will have a muon tag. This fraction rises to over 90% by 10 TeV. This will enable us to examine the muon content of observed signals, such as from the Crab.

The ability to detect the Crab is a good benchmark of the performance of MILAGRO. Taking into account the variation of the trigger efficiency and angular resolution with energy, we have calculated the statistical significance of the signal that would be observed by MILAGRO for one year of operation. The result is 5 standard deviations, assuming the spectrum measured by the Whipple[9] and THEMISTOCLE[10] groups. The shape of the

Čerenkov light image for the Whipple signal from the Crab below 4 TeV appears to behave as expected for gamma-ray-induced showers. One might then expect that the showers from the Crab would also be muon poor. If this is the case, rejecting events with one or more muon will enhance the Crab signal from 5 to about 7 standard deviations, for one year of data.

A distinct advantage of the MILAGRO detector is that it will be able to observe the Crab, and many other potential sources, on a daily basis year around. MILAGRO would be able to detect with a significance of 5 standard deviations a one day burst flux from the Crab that is 19 times the DC flux.

In summary, MILAGRO will be capable of bridging the gap between existing air-Čerenkov and extensive air-shower detectors and studying the muon content of air showers down to about 1 TeV. It can observe the Crab signal with high significance within its first year of operation and scan the entire northern sky for sources. MILAGRO will be a powerful new tool in gamma-ray astrophysics.

ACKNOWLEDGMENTS

The author wishes to thank the conference organizers for a rewarding week in Dallas and the MP Division of Los Alamos National Laboratory for its hospitality. This work is supported in part by the National Science Foundation, Los Alamos National Laboratory, the U.S. Department of Energy, the Institute of Geophysics and Planetary Physics of the University of California, and the National Academy of Sciences.

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