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Above 40 TeV with the CYGNUS Array

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**A Continuous Watch of the Northern Sky
Above 40 TeV with the CYGNUS Array**

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The aim of the project has been to continuously monitor the northern sky for transient high-energy gamma-ray emission from astrophysical sources. Potential objects of such emission include gamma-ray bursts and flares from active galaxies. At the start of this project, the CYGNUS extensive air shower array was used for the monitoring; CYGNUS has an energy threshold of ~ 40 TeV. In August, 1996, the CYGNUS data-acquisition computer suffered a fatal hardware problem so data-taking with the array ended. The Milagrito detector, which is much more sensitive than CYGNUS, started taking data in February 1997 and has continued the sky monitoring. We are presently honing reconstruction algorithms for Milagrito. When this is complete, the data taken since February will be analyzed for transient emission.

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Background and Research Objectives

The study of transient phenomena in the universe on time scales from seconds to days over an energy range from radio to very-high-energy gamma rays is a new field of research. Potential objects of interest include gamma-ray bursts, active galaxies and quasars, supernovae, variable and flare stars, comets, and asteroids; these are some of the most exciting objects in the cosmos. Studies to date have shown very exciting results. For example, a chance observation detected a large flare in very-high-energy (> 1 TeV) emission from Markarian 501, an active galaxy. A world-wide campaign this summer found that this object emits very-high-energy gamma rays that vary in intensity by nearly an order of magnitude over time scales of hours; this is remarkable considering that the central engine providing the power for this emission is believed to be a super-massive (about a billion solar-mass) black hole. Figure 1 shows the day-to-day flux of high-energy gamma rays from Markarian 501 from several air Cerenkov telescopes[1]. Note that there are no observations during periods of bright moonlight (and cloudy nights) as air Cerenkov telescopes require clear, dark skies. The study of transient astrophysical events is difficult because it requires that the telescopes be dedicated to that sole purpose. The exciting observations of Markarian 501 are a fortuitous accident; most of the sky is not monitored for transient phenomena. Air Cerenkov telescopes can only observe a small region of the sky at one time.

Air shower arrays (such as CYGNUS) are able to observe the entire overhead sky at once, 24 hours per day every day. Thus, they are good instruments to search for transient emission, especially from unknown directions, such as from gamma-ray bursts. However the CYGNUS array has a significantly higher energy threshold than air Cerenkov telescopes (~ 40 TeV vs. ~ 1 TeV). The Milagro gamma-ray detector, under construction at Fenton Hill, will be the first detector to combine the all-sky, 24-hour-per-day attributes of CYGNUS with an energy threshold below 1 TeV; thus it is much better suited to searches for transient emission.

This LDRD project has been to continuously monitor the northern sky for transient high-energy emission. During the first two years, the CYGNUS array was used; no evidence for transient emission was observed during that period. During this last year, the Milagrito detector, a prototype for Milagro, has been used for the monitoring.

Importance to LANL's Science and Technology Base and National R&D Needs

Transient astrophysical emission has long been of great interest to LANL astrophysicists. Gamma-ray bursts (GRBs) were discovered at Los Alamos with data

taken with the Vela satellite; GRBs remain amongst the most interesting and enigmatic objects in the heavens. Data from the ALEXIS satellite has also uncovered unexplained transient x-ray flashes. The University of California Intercampus Institute for Nuclear and Particle Astrophysics and Cosmology (INPAC), of which Los Alamos is a member, is focused on transient astronomy and is interested in establishing an observatory dedicated to this topic at Fenton Hill; INPAC has funded an optical telescope, REACT, to be sited at Fenton Hill for this purpose.

Milagro is one of this country's major projects in nuclear and particle astrophysics; it is jointly funded by the NSF, DOE, LANL, and the University of California. Milagro is a project that involves scientists from eight universities and Los Alamos. The technology used in Milagro (detection of Cerenkov light produced in a large volume of water) is basically the same used in several other major detectors (LSND, BooNE, SNO, SuperK) that involve LANL physicists. There has been a healthy sharing of knowledge and ideas between these projects. For example, the Milagro collaboration developed a new technique to construct reflecting underwater surfaces (using Tyvek); this technique has been adopted by the SuperK group and is part of their detector.

Scientific Approach and Accomplishments

High-energy cosmic gamma rays interact high in the earth's atmosphere producing extensive air showers. Instruments such as CYGNUS and Milagro detect particles produced in these air showers that survive to ground level; the particles at ground level are predominantly electrons, positrons, and photons. Because this is not an optical technique, arrays can operate all day and night in any weather conditions. The direction of the incident gamma ray is reconstructed for each event by measuring the relative time at which each detector element is struck; the energy of the primary gamma ray can be crudely determined by measuring the pulse height in each detector element. In the CYGNUS array, the detector elements are widely spaced scintillation counters. Milagro and Milagrito use photomultiplier tubes immersed in a large, covered pond of water.

The CYGNUS array was operated in this project from October, 1994 through August, 1996. The data were reconstructed on-line. Each month, the data were analyzed for any strong evidence of episodic emission from anywhere in the sky; none was found. In addition, the data were scanned at times that satellite-based instruments detected gamma-ray bursts within the CYGNUS field of view; again no evidence of episodic emission was detected in the CYGNUS data set. These results have been presented informally at conferences and workshops. They have not been published because they do not significantly improve the upper limits for such emission previously published by the

CYGNUS group [2,3,4]. This is partially because no strong gamma-ray burst was observed within the CYGNUS field of view during this period.

In August, 1996, the CYGNUS data-acquisition computer suffered a fatal hardware error. Rather than replacing the computer (in fact, this would have been difficult as this type of computer is no longer available), we decided to continue the monitoring of the northern sky with the Milagrito detector, which was about to be installed in a pond at Fenton Hill. The 225 photomultiplier tubes were installed in September, 1996: the on-line code was then written and debugged. In February, 1997 we began continuous operation of Milagrito, which has been taking data with $\sim 75\%$ live time since February. Over 3 billion events have been recorded. In the time since data-taking with Milagrito began, we have been developing algorithms to calibrate the instrument and reconstruct events; when this is complete, the data will be analyzed for episodic emission, especially from Markarian 501, which is known to be flaring during this period. In fact, Milagrito will be the only instrument capable of continuing to monitor Markarian 501 as it rises in the daytime in the fall.

Figure 2 shows the difference in reconstructed angle for events from Milagrito obtained by splitting the array into two interleaved halves and reconstructing the event separately from each half; this indicates an angular resolution of $\sim 0.5^\circ$. This technique of measuring the angular resolution is not sensitive to systematic errors. Nevertheless, it does indicate that the reconstruction algorithms are working reasonably well.

In addition, we analyzed data taken with a small prototype detector that acquired data in the Milagro pond with 35 photomultiplier tubes (this prototype was called "Milagrissimo") over the winter of 1995-96. Again, no evidence of episodic emission was observed. These results were presented at the XXV International Conference on Cosmic Ray Physics, in Durban, South Africa (1).

Publication

1. Berley, D., *et. al.*, "Results from the Milagrissimo Air Shower Detector", Proceedings of the XXV International Cosmic Ray Conference, **3**, 285 (1997).

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- [2] Biller, S. *et. al.*, "Search for Ultra-High-Energy Point-Source Emission over Various Timescales," *Astrophys. J.* **423**, 714 (1994).
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- [4] Allen, G. E., *et. al.*, "Search for Ultra-High-Energy Radiation from Gamma-Ray Bursts," in *Proc. of the International Cosmic-Ray Conference*, Rome (1995), **2**, 124 (1995).

Figure 1: The daily flux of gamma rays above ~ 400 GeV observed by three air Cerenkov telescopes: CAT in the Pyrenees, Whipple in Arizona, and HEGRA in the Canary Islands. The abscissa is the Mean Julian date and covers the period from March, 1997 through July, 1997.

Figure 2. The distribution of the difference in space angle reconstructed from two independent, interleaved arrays of photomultiplier tubes in the Milagrito detector. The inferred angular resolution for the entire detector is roughly one-half of this angle.