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TeV OBSERVATIONS OF MARKARIAN 501 WITH THE MILAGRITO WATER CERENKOV DETECTOR

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ABSTRACT

The Milagrito water Cerenkov detector near Los Alamos, New Mexico, was operated as a sky monitor at energies of a few TeV between 1997 February and 1998 May, including the period of the strong, long-lasting 1997 flare of Markarian 501. Milagrito served as a test run for the full Milagro detector. An event excess with a significance of 3.7 σ from Markarian 501 was observed, in agreement with expectations.

Subject headings: BL Lacertae objects: individual (Markarian 501) — gamma rays: observations

1. INTRODUCTION

Very high energy (VHE) γ-ray astronomy is the study of the sky at energies above 100 GeV. To date, four Galactic and four extragalactic sources have been identified as VHE sources (see Ong 1998 and Hoffman et al. 1999 for recent reviews). The four extragalactic sources, Markarian 421 ($z = 0.031$; Punch et al. 1992), Markarian 501 ($z = 0.034$; Quinn et al. 1996), 1ES 2344+514 ($z = 0.044$; Catanese et al. 1998), and PKS 2155−304 ($z = 0.117$; Chadwick et al. 1999), are relatively nearby objects of the BL Lacertae subclass of active galactic nuclei. A characteristic feature of BL Lac objects is their rapid flux variability at all wavelengths. Flaring activity at TeV energies has been observed from both Mrk 421 and Mrk 501, ranging from variability timescales of minutes (Gaidos et al. 1996) to months (Protheroe et al. 1997).

Source detections and analyses at VHE energies are currently dominated by the highly successful atmospheric Cerenkov technique. Cerenkov telescopes are excellent tools for the detailed study of point sources, and their sensitivity has been improved significantly over the past few years. Strong flaring activity of Mrk 421 and Mrk 501 can be detected with less than an hour of observation time per night.

To complement the pointed atmospheric Cerenkov telescopes, there is a strong case for wide-aperture instruments monitoring the sky with a high duty cycle and performing an unbiased search for new sources and source classes. The price to pay for overcoming the limitations of atmospheric Cerenkov telescopes is a loss in sensitivity for individual sources. To date, no unambiguous detection of a steady TeV source has been established with an air shower detector.

The Milagro water Cerenkov detector (McCullough et al. 1999) near Los Alamos, New Mexico, at latitude 35°.9 north and longitude 106°.7 west, a first-generation all-sky monitor operating with an effective energy threshold below 1 TeV, started recording data in 1999. Milagrito (Atkins et al. 1999), a smaller, less sensitive prototype of the top layer of Milagro, recorded data between 1997 February and 1998 May. Milagrito was located at the same site and served mainly as a test run for studying specific design questions for the Milagro detector. Nevertheless, Milagrito operated as a fully functioning detector and started recording data during the strong, long-lasting flare of Mrk 501 in 1997. During this flare, Mrk 501 was studied intensively with several atmospheric Cerenkov telescopes (see Protheroe et al. 1997). Detailed flux and spectral studies have been published from data recorded by the Whipple telescope on Mount Hopkins (Arizona) between 1997 February and June (Samuelson et al. 1998) and the HEGRA stereo system of Cerenkov telescopes on La Palma (Canary Islands) between 1997 March and October (Aharonian et al. 1999). Although they do not cover the same observation times, the average fluxes measured by Whipple and HEGRA agree extremely well in both shape and magnitude, and they both indicate an energy spectrum that deviates significantly from a simple power law. Using an average flux as measured by Whipple,

$$J_\gamma(E) = (8.6 \pm 0.3 \pm 0.7) \times 10^{-7} \times \left(\frac{E}{\mathrm{TeV}}\right)^{-2.20 \pm 0.04 \pm 0.05 - (0.45 \pm 0.07) \log (E/\mathrm{TeV})} \ \mathrm{m^{-2}\ s^{-1}\ TeV^{-1}}, \tag{1}$$

simulations suggest that the observation of a statistically significant excess from Mrk 501 is within the reach of Milagrito.

Observations with atmospheric Cerenkov telescopes do not

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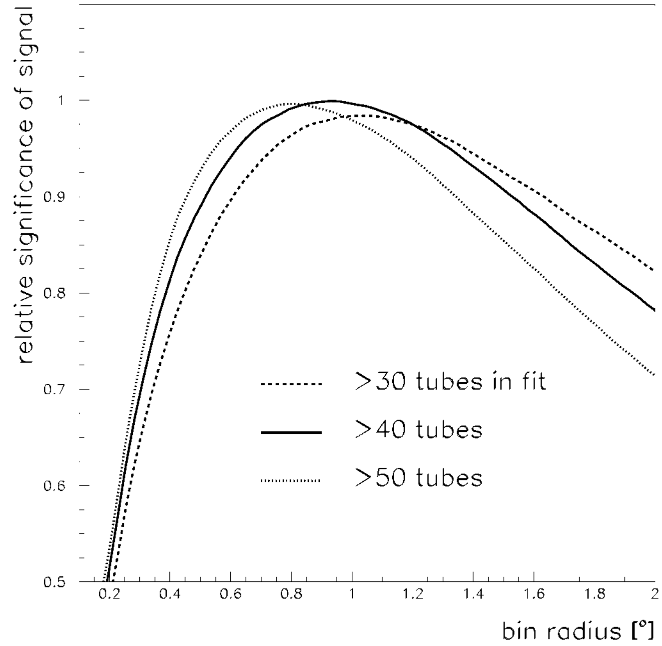

FIG. 1.—The relative significance of a signal from a point source at the position of Mrk 501 as a function of the source bin radius for various cuts in the number of tubes in the shower plane fit.

cover the time between 1997 October and 1998 February, when Mrk 501 was visible only during the daytime. When atmospheric Cerenkov telescopes resumed observations in 1998, they observed a relatively high flux for a few days at the beginning of March, but the flux quickly decreased and was considerably lower for the rest of 1998 than in 1997 (Quinn et al. 1999). As an instrument that is insensitive to sunlight, Milagrito continued to monitor Mrk 501 in late 1997 and early 1998. In this Letter, we present the results of an analysis of Milagrito data on Mrk 501.

2. THE MILAGRITO DETECTOR

Since source spectra tend to be falling power laws, a large detector area is essential for a sufficient rate from point sources in the VHE region. The restriction to Earth-bound detectors makes the detection of the primary γ-rays considerably more complicated, since the primary particle generates a cascade of secondary particles in the atmosphere, an "air shower." Air shower detectors have to reconstruct the properties of the primary γ-ray from the secondary particles reaching the detector level, and any γ-ray signal has to be observed in the presence of a large isotropic background from cosmic rays. To achieve sufficient sensitivity at TeV energies, a high-altitude location and the ability to detect a large fraction of particles falling within the detector area are crucial.

Milagrito was a water Cerenkov detector of size 35 m × 55 m × 2 m, located at 2650 m above sea level (750 g cm^{-2} atmospheric overburden) in the Jemez Mountains near Los Alamos, New Mexico. The project took advantage of an existing man-made rectangular 21 million liter pond. A layer of 228 submerged photomultiplier tubes on a 2.8 m × 2.8 m grid detected the Cerenkov light produced by secondary particles entering the water, allowing the shower direction and thus the direction of the primary particle to be reconstructed. The detector and the detector simulation used to study its sensitivity are described in detail elsewhere (Atkins et al. 1999).

The water Cerenkov technique uses water both as the detection medium and to transfer the energy of air shower photons to charged particles via pair production or Compton scattering. Consequently, a large fraction of shower particles can be detected, leading to a high sensitivity even for showers with primary energies below 1 TeV.

Milagrito operated with a minimum requirement of 100 hit tubes per event, where the discriminator threshold was set so that a photomultiplier signal of ∼0.25 photoelectrons would fire the discriminator. The direction of the shower plane is determined with an iterative least-squares (χ^2) fitter using the measured times and positions of the photomultiplier tubes. Only tubes with pulses larger than 2 photoelectrons are used in the fit, and in subsequent iterations, tubes with large contributions to χ^2 are removed. The resulting angular resolution is a strong function of the number of tubes remaining in the final iteration of the fit, n_{fit}. If no restriction is made on n_{fit}, Monte Carlo simulations indicate that the median space angle between the fitted and the true shower direction is about 1°.1 for a source at the declination of Mrk 501.

The optimal cut on n_{fit} and the optimal bin size for a point-source search depend on the observed n_{fit} distribution and the angular resolution as a function of n_{fit}. Since the point-spread function of Milagrito is not well characterized by a two-dimensional Gaussian, the standard formulae are inappropriate. To estimate the angular resolution as a function of n_{fit}, the detector is divided into two independent, interleaved portions (similar to a checkerboard). For each band of n_{fit}, the distribution of space-angle differences between the two portions of the detector are stored. In the absence of systematic effects, these distributions can be interpreted as twice the point-spread function of the detector for the given band of n_{fit} (Alexandreas et al. 1992). Under the assumption that the point-spread function for γ-ray showers is identical to that of hadron-induced air showers, one can use the above distributions to determine the optimal cut on n_{fit} and the optimal size of the angular bin. Figure 1 shows the expected significance of a source as a function of angular bin size for three different cuts on n_{fit}. The analysis indicates that requiring $n_{\mathrm{fit}} > 40$ with a bin size of radius 1°.0, which on average contains 57% of the source events, is optimal for a binned analysis. As shown in Figure 1, for a rather wide range of cuts, the significance of an excess depends only weakly on the chosen source bin size.

Since the detector is much smaller than the typical lateral size of a shower, the shower core, i.e., the point where the primary particle would have struck the detector had there been no atmosphere, is outside the sensitive detector area for a large fraction of showers fulfilling the trigger condition. Assuming a differential flux following $E^{-2.8}$ for the proton background and $E^{-2.5}$ for a typical γ-source, 16% of the proton showers and 21% of the γ-showers triggering the Milagrito detector have their cores on the pond. This leads to a broad distribution of detected events with no well-defined threshold energy. Monte Carlo simulations using the Mrk 501 spectrum given in equation (1) predict a distribution starting at energies as low as 100 GeV, with 90% of the detected events having an energy in excess of 0.8 TeV. The median energy of detected showers depends on the declination δ and the spectral index of the source, and typical values are 3 TeV for $\delta = 39°.8$ (Mrk 501) and 7 TeV for $\delta = 22°.0$ (Crab Nebula, assuming an $E^{-2.5}$ spectrum).

Detector performance is best evaluated by observations of well-known sources. The standard candle of VHE astronomy is the Crab Nebula. Simulations indicate that the expected sta-

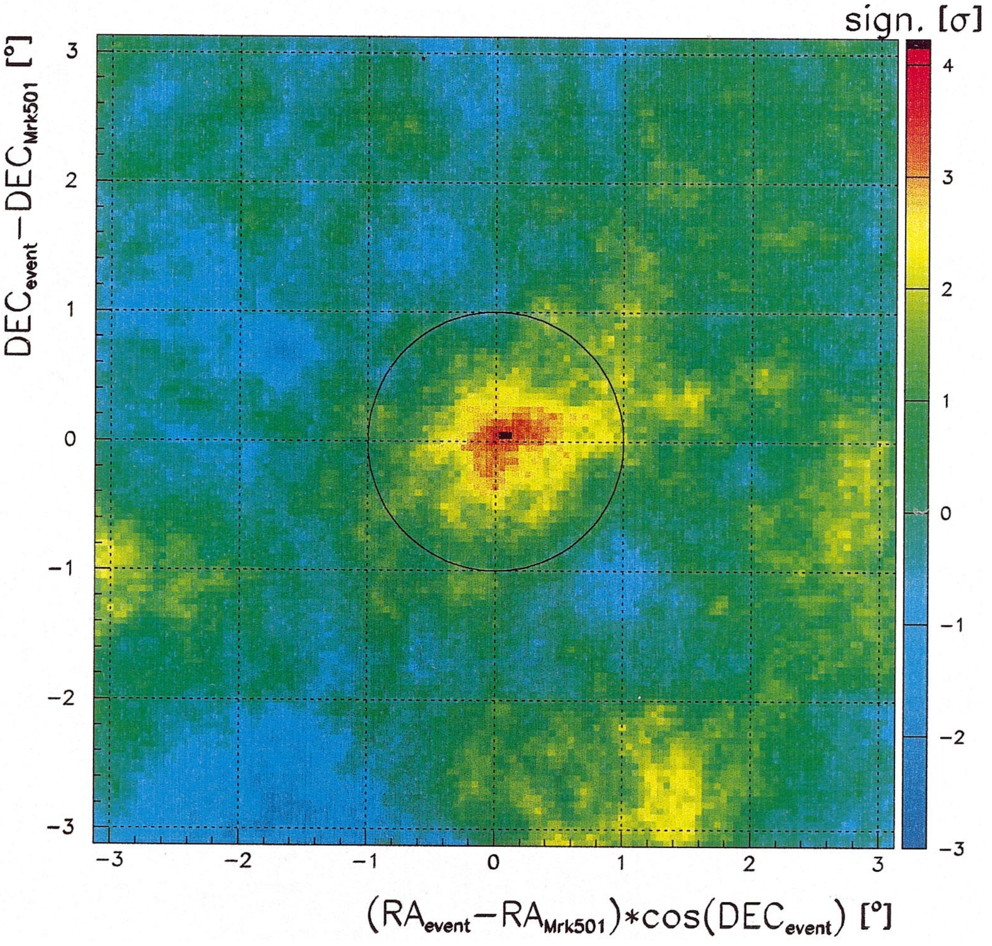

FIG. 2.—The significance for an event excess as a function of right ascension and declination in a 6° × 6° region with the Mrk 501 position [R.A. = 253°.468, decl. = 39°.760 (J2000)] in the center. For each bin, the significance is calculated for the area of the circle with radius 1°.0 and the bin center as the central point; thus, neighboring bins are highly correlated. The circle indicates the source bin.

tistical significance of the excess above background from the Crab Nebula in Milagrito is too small to be used for testing Milagrito's performance, and indeed no significant excess from this source was observed. However, the large average flux of Mrk 501 during its flaring state in 1997 results in an expected event rate from Mrk 501 that is 3.6 times the Crab rate for Milagrito. Mrk 501 can therefore be used to measure the sensitivity of Milagrito and to test the reliability of the detector simulation.

3. RESULTS

Milagrito started recording data on Mrk 501 from 1997 February 8 to 1998 May 7. The effective exposure time was about 370 days, with most of the downtime being due to power outages, detector maintenance, and upgrades. Milagrito started operation with about 0.9 m of water above the tubes. The water level was increased starting in 1997 November in order to study how the sensitivity changes with water depth. The trigger rate was about 300 Hz with 0.9 m of water and increased to 340 Hz (400 Hz) at a depth of 1.5 m (2.0 m).

The measured rate of 2420 ± 80 reconstructed events per day for a 0.9 m water depth in a typical bin with 1°.0 radius at the same declination as Mrk 501 is in good agreement with the predicted rate of 2460^{+160}_{-90} events per day from protons, helium, and CNO nuclei (the error accounts for the uncertainty in the measured flux). The contributions from He and CNO to this predicted rate are 27% and 4%, respectively.

The isotropic cosmic-ray background flux exceeds the γ-signal from Mrk 501 by several orders of magnitude. The expected background flux in the source bin must be subtracted from the measured one in order to obtain the number of excess events from the source. Since the background in the source bin depends on its exposure and on the detector efficiency in local angular coordinates, the background is calculated directly from the data (Alexandreas et al. 1993). For each detected event, "fake" events are generated by keeping the local zenith and azimuth angles (θ and ϕ) fixed and by calculating new values for right ascension using the times of 30 events randomly selected from a buffer that spans about 2 hr of data recording. The background level is then calculated from the number of fake events falling into the source bin. By using at least 10 fake events per real event, the statistical error on the background can be kept sufficiently small.

Figure 2 shows the significance of the observed signal as a function of right ascension and declination in a 6° × 6° region with the Mrk 501 position in the center. For each bin, the significance is calculated for the area of the circle with radius 1°.0 and the bin center as the central point; hence, neighboring bins are highly correlated.

At the source position, 918,954 events are observed with an average expected background of 915,330 ± 250 events. The excess of 3624 ± 990 events corresponds to a significance of 3.7 σ. We interpret this result as a reconfirmation of Mrk 501 as a TeV γ-ray source during this period. The corresponding excess rate averaged over the lifetime of Milagrito is 9.8 ± 2.7 day^{-1}. The excess rate measured between 1997 February and October 1 can be compared directly with the γ-rate expected using the average flux measured by atmospheric Cerenkov telescopes during this period. Using the flux given in equation (1), Monte Carlo simulations of a full-source transit predict a γ-rate of 12.5 ± 3.8 day^{-1}, which is in good agreement with the measured rate during this period of 13.1 ± 4.0 day^{-1}.

Figure 3 shows excess divided by background for the lifetime of Milagrito. At Milagrito's level of sensitivity, the flux is consistent with being constant in time.

The analysis was extended to 10 other nearby blazars ($z < 0.06$) in Milagrito's field of view, including Mrk 421, but Mrk 501 remains the only analyzed source with a significance in excess of 3 σ. Results from this blazar sample are reported elsewhere (Westerhoff et al. 1999).

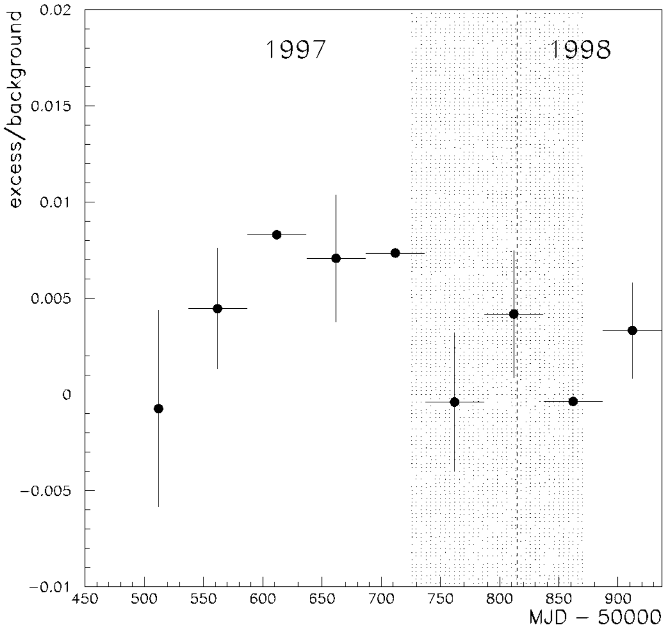

FIG. 3.—The fractional event excess from Mrk 501 as a function of time. The shaded area indicates the time period for which no data from atmospheric Cerenkov telescopes are available.

4. CONCLUSIONS AND OUTLOOK

Milagrito, the first TeV air shower detector based on the water Cerenkov technique, observed an excess with a statistical significance of 3.7 σ from the direction of Mrk 501 between 1997 February and 1998 May. The excess is in agreement with expectations based on simulations and indicates that the technique is working as anticipated.

Milagrito served as a prototype for the full Milagro detector. In its final stage, Milagro has a size of 60 m × 80 m × 8 m and two layers of photomultiplier tubes, an upper layer with 450 tubes at a depth of 1.5 m and an additional layer with 273 tubes at a depth of 6.2 m. With its larger effective area and the ability to reject some of the cosmic-ray background, Milagro will be at least 5 times as sensitive as Milagrito. Data recording began in early 1999.

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