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Study of Active Galactic Nuclei at TeV Energies with Milagrito

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Abstract. The Milagro water Cherenkov detector near Los Alamos, New Mexico, is the first air shower detector capable of continuously monitoring the γ-ray sky at energies between 250 GeV and 20 TeV. In contrast to air Cherenkov telescopes, Milagro has a high duty cycle and a large field of view and will generate the first TeV sky map and study transient sources. One of the primary goals is the search for, and study of, AGN at TeV energies, giving insight into particle acceleration mechanisms and providing information on the strength of the extragalactic infrared background. This paper summarizes preliminary results on the observation of nearby blazars based on data taken between February 1997 and April 1998 with a smaller, less sensitive prototype, Milagrito.

1. Introduction

The launch of the Compton Gamma-Ray Observatory (CGRO) by NASA in 1991 led to an enormous influx of data from 50 keV to 30 GeV. Much attention has focussed on Active Galactic Nuclei (AGN), the class of galaxies with strong non-thermal activity in their center. EGRET, aboard CGRO, has detected γ-emission from about 60 AGN [1, 2], thus establishing them as the most luminous class of extragalactic objects at energies above 100 MeV.

Out of the variety of different types of AGN, EGRET only detects *blazars*, a subclass of AGN that comprises radio-loud, flat-spectrum radio quasars and BL Lacertae objects. Blazars are characterized by featureless, polarized continuum emission and a rapid variability on time scales of hours to days at most wavelengths.

Although the power-law spectra of EGRET blazars suggest an observable flux even at TeV energies, only three extragalactic objects, Mrk 421 (z=0.031), Mrk 501 (z=0.034), and 1ES 2344+514 (z=0.044), all relatively nearby BL Lacs, have been unambiguously detected at TeV energies [3, 4, 5]. None of these BL Lacs are strong EGRET sources (1ES 2344+514 has in fact not been detected by EGRET), and strong EGRET sources at high redshifts like 3C 279 at z=0.54 have not been detected at TeV energies.

The small number of established sources and the rather fragmentary knowledge of the TeV sky may in part be due to the fact that current observation techniques are limited in their ability to perform an unbiased, systematic and continuous search for TeV sources. While satellite experiments are an optimal tool in the MeV to GeV range, the large effective area needed for sufficient rates at TeV energies requires earth-bound detectors; as a consequence, the primary particle can no longer be detected directly, but has to be reconstructed from the secondary particles of the air shower cascade or the Cherenkov light produced by relativistic particles in the cascade.

At this point, the most sensitive method is the imaging atmospheric Cherenkov technique [6] pioneered by the Whipple telescope [7] on Mt. Hopkins, Arizona. Cherenkov telescopes are *pointed* instruments with a field of view of the order of 3°. The detection of Cherenkov light in the atmosphere requires clear, dark nights, leading to a very low duty cycle of about 10 %. Optimized for the detailed study of individual sources, Cherenkov telescopes are not able to continuously monitor large parts of the sky for transient phenomena, and a blind search for unknown sources and source classes is difficult. There is, therefore, a strong case for a high duty cycle, large aperture instrument with sufficient sensitivity. The observation technique must exploit the *particle content* of air showers rather than the Cherenkov light.

A first-generation all-sky monitor operating at energies below 1 TeV, the Milagro [8] detector located 2600 m above sea level near Los Alamos, New Mexico, at latitude 35.9° N, is nearing completion. Milagro is a water Cherenkov detector of size $60 \times 80 \times 8\,\mathrm{m}^3$. Two layers of photomultiplier tubes detect the Cherenkov light produced by secondary particles entering the water. The first layer, with 450 tubes on a $3 \times 3\,\mathrm{m}^2$ grid at a depth of 1.5 m, allows the shower direction and thus the direction of the primary particle to be reconstructed, while the second layer with 273 tubes at a depth of 7.0 m primarily detects the penetrating component of air showers, *ie.* muons, hadrons, and highly energetic electromagnetic particles. Recognizing these "hot spots" in the shower image provides a tool to decrease the hadronic background which outnumbers the γ-ray signal by several orders of magnitude.

The full two-layer detector will start data taking in early 1999. A smaller, less sensitive prototype, Milagrito, has taken data between February 1997 and April 1998. Milagrito, a one-layer detector of size $35 \times 55 \times 2\,\mathrm{m}^3$ with 228 photomultiplier tubes on a $3 \times 3\,\mathrm{m}^2$ grid at a rather shallow depth of 0.9 m, does not provide an efficient separation of γ-ray showers from the hadronic background ("γ/hadron separation") and served mainly as a test run for this relatively new detection technique. This prototype has, however, taken data during a very intense and long-lasting flare of Mrk 501 in 1997 [9]. The search for Mrk 501 and other nearby blazars is therefore a challenging first step in evaluating the detector performance.

This paper summarizes the results from Milagrito data analysis for 11 nearby blazars ($z \leq 0.06$) in its field of view.

2. The Blazar Sample

One of the main features of blazars is their variability at all wavelengths. Variability on a time scale of hours has been observed at TeV energies [10]. Upper limits on the size of the emitting region derived from variability studies imply that an enormous luminosity is released from a very small volume. This has motivated the current understanding of AGN as accreting supermassive black holes of $\sim 10^8$-10^{10} solar masses with bipolar jets. The γ-radiation originates in these jets. Radio observations indicate that blazars are AGN with the radio jets at small angles to the line of sight, leading to Doppler-boosted emission and kinematic effects like the (apparent) superluminal motion of radio knots in the jets.

While this picture is widely accepted, the acceleration mechanisms leading to TeV emission from blazars are still a subject of lively debate. Whereas the low energy emission from radio to X-ray wavelengths is generally interpreted as synchrotron radiation of relativistic electrons in the jet, both electron- and proton-based models have been suggested to explain the emission in the GeV to TeV region. In electron-based models, the relativistic electrons that cause the synchrotron radiation also upscatter the low energy photons in the jet (synchrotron-self-Compton or SSC model [11]) or ambient photons (external Compton or EC models [12]) into high energy photons by inverse Compton scattering.

In proton-based models (proton-initiated-cascade or PIC models [13]), protons enter the jet. These protons are accelerated up to energies of 10^{18} eV [14] where photo-production of pions (via $\Delta(1232)$) is the dominant cooling process. This induces an electromagnetic cascade in the jets, and the high-energy γ-rays eventually escape once their energy is below the critical energy and the jet is no longer opaque.

In addition to increasing our understanding of the acceleration mechanisms in AGN, the study of blazars also offers a tremendous potential for cosmology and astrophysics: photons from sources at cosmological distances suffer absorption by e^+e^--pair production with photons of the diffuse extragalactic background light. It has been suggested [15] that one might infer the diffuse extragalactic background at wavelengths from ~ 0.1 to $100\,\mu$m, *ie.* in the optical to infrared region, by measuring the expected cutoff in the source spectra of TeV sources. The infrared regime is of particular interest, as direct measurements of the infrared background are notoriously difficult because of local effects and dust. In addition, Primack, Bullock, Somerville and MacMinn [16, 17, 18] have shown that semi-analytical models of galaxy formation allow an estimation of how the extragalactic background light and thus the attenuation of VHE γ-rays depend on input assumptions like the history of star formation and the stellar initial mass function.

source	z	name
0310+4104	0.028	
0430+052	0.033	3C 120.0
0554+5328	0.036	
1101+384	0.031	Mrk 421
1133+704	0.046	Mrk 180
1652+398	0.034	Mrk 501
1727+502	0.055	I Zw 187
1807+698	0.051	3C 371
1959+650	0.047	
2321+419	0.059	
2344+513	0.044	

Table 1. The blazar sample.

To fully utilize these methods, it is crucial to be able to separate external absorption from internal absorption at the source, a requirement which can only be met with a sufficiently large number of sources. The ability to systematically search for yet unknown sources and source classes is an advantage of large-aperture instruments like Milagro. While the overall goal is to generate the first TeV sky map, the search for TeV γ-ray emission from known nearby blazars is an important first step.

Theory-guided blazar searches have been performed by Cherenkov telescopes. However, the γ-ray variability of these sources make a *continuous* observation extremely desirable. The following analysis concentrates on all known blazars in the field of view of Milagrito, *ie.* blazars with a declination between 0° and 70°, and a redshift $z \leq 0.06$ (see [19, 20] and references therein for blazar catalogs). The discussion of whether blazars seen at TeV energies are equivalent to so-called high-frequency peaked BL Lacs (HBLs) [21] is disregarded here. The fact that the three established TeV blazars belong to this class of BL Lacs is interesting, but not statistically compelling. Table 1 lists the resulting blazar sample.

Simulations indicate that Milagrito's expected annual significance for the Crab nebula, a well-studied "standard candle" of TeV astronomy with a steady flux of [22]

$$J_\gamma(E) = (3.20 \pm 0.17 \pm 0.6) \times 10^{-7}\, E_{\mathrm{TeV}}^{-2.49 \pm 0.06 \pm 0.04}\, \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}, \quad (1)$$

is less than $2\,\sigma$. A blazar detection with a sufficiently high significance can therefore only be expected if the source (during the lifetime of the detector) had an average flux in excess of the Crab flux. During its flare in 1997, Mrk 501 has been intensively studied with air Cherenkov telescopes. The average fluxes measured by Whipple [9] and the HEGRA stereo system of air Cherenkov telescopes [23], although not covering the same observation times, agree extremely well both in shape and magnitude, and they both indicate a significant curvature of the energy spectrum. Using an average flux as measured by Whipple,

$$\begin{aligned} J_\gamma(E) = {} & (8.6 \pm 0.3 \pm 0.7) \times 10^{-7} \\ & E_{\mathrm{TeV}}^{-2.20 \pm 0.04 \pm 0.05 - (0.45 \pm 0.07) \log_{10} E}\, \mathrm{m}^{-2}\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}, \end{aligned} \quad (2)$$

simulations predict the expected integral γ-rate from Mrk 501 to be 3.6 times the Crab

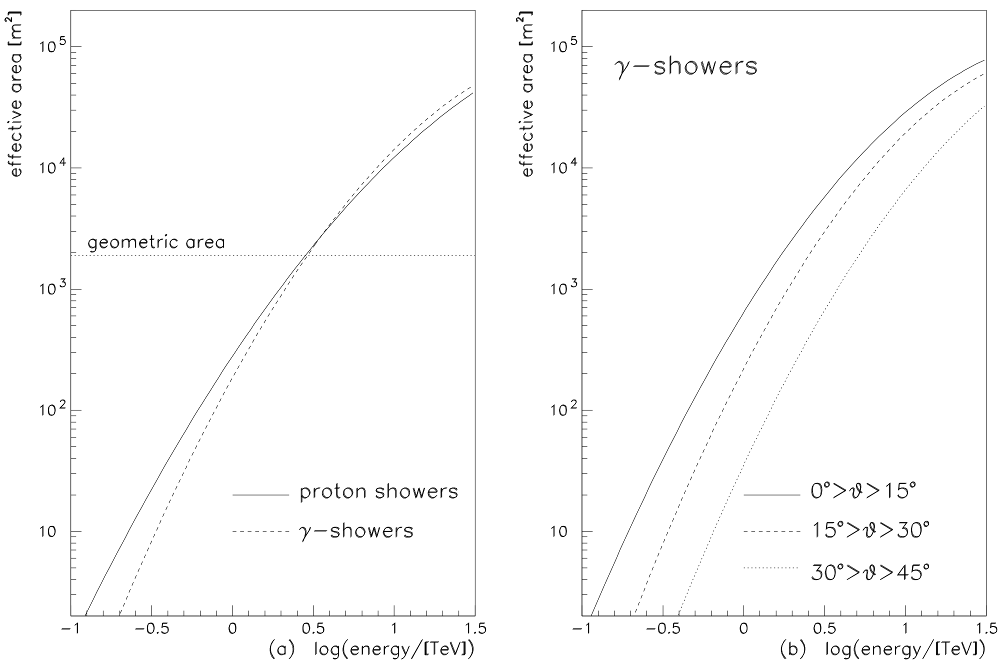

Figure 1. (a) Effective area as a function of the primary energy for proton- and γ-induced showers in Milagrito for reconstructed showers (zenith angle range $0^\circ \leq \theta \leq 45^\circ$). (b) Effective area for γ-showers for various zenith angle ranges.

rate for Milagrito.

3. Milagrito Simulation

Key detector parameters such as effective area, angular resolution, and median energy of detected γ-showers are determined by a full detector simulation, which is performed in two steps. For the air shower cascade in the Earth's atmosphere, we use CORSIKA (version 5.61) [24], a simulation package provided by the KASCADE group [25]. The simulation of the Milagrito detector is based on the GEANT package (version 3.21) [26]. GEANT includes electromagnetic and hadronic interactions and the production of Cherenkov photons.

For water detectors the size of Milagrito, both absorption and scattering of Cherenkov photons in the water play a fundamental role and are the most delicate parameters of the simulation. The type and the amount of scattering is difficult to estimate and to simulate. While the attenuation length of the water is frequently monitored, the individual contributions of scattering and absorption have at present not been tackled and remain a major uncertainty in the simulation.

Figure 1 (a) shows the effective area A_{eff} of Milagrito for both γ- and proton-induced air showers as a function of the energy of the primary particle. As a large fraction of showers fulfilling the trigger condition have their core outside the sensitive

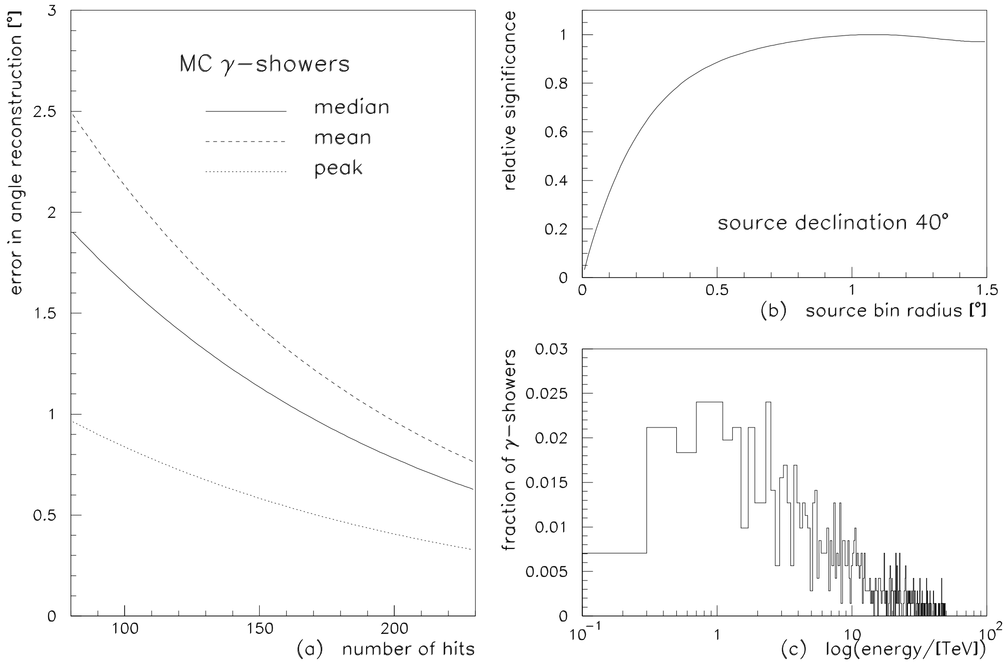

Figure 2. (a) Angular resolution and (c) energy distribution of γ-showers triggering Milagrito. (b) shows the relative source sensitivity as a function of the source bin radius.

detector area, the effective area is larger than the geometrical area above $\sim 3\,\mathrm{TeV}$. In fact, only 16 % of the proton showers and 21 % of the γ-showers triggering the Milagrito detector have their core on the pond. It is noteworthy that at energies $\leq 2\,\mathrm{TeV}$, the effective area for proton-induced showers is larger than for γ-showers. This is related to the fact that γ-induced (thus almost purely electromagnetic) showers are usually more laterally confined so the area covered by the particles reaching detector altitude is smaller than for hadron-induced showers, which tend to have "hot spots" with high particle density at large distances to the shower core. At energies above $\sim 5\,\mathrm{TeV}$, the larger effective area for γ-induced showers provides an intrinsic γ/hadron separation. Figure 1 (b) shows how the effective area depends on the zenith angle θ.

The water Cherenkov technique has a very high efficiency in detecting shower particles and therefore provides a very low energy threshold. As a downside, the angular resolution is affected by low energy particles reaching the detector late as compared to the shower front. In addition, Cherenkov photons in water are emitted with a rather large angle (41°) to the particle direction. Horizontal light in conjunction with scattered and reflected light leads to a fraction of photons reaching the photomultipliers relatively late †.

To illustrate the angular resolution of Milagrito, Figure 2 (a) shows the mean and

† To decrease this "late light tail" which limits the angular resolution, the photomultipliers for Milagro have been equipped with cones. Reflective on the inside, these "baffles" increase the collection area for direct light while blocking the late horizontal component.

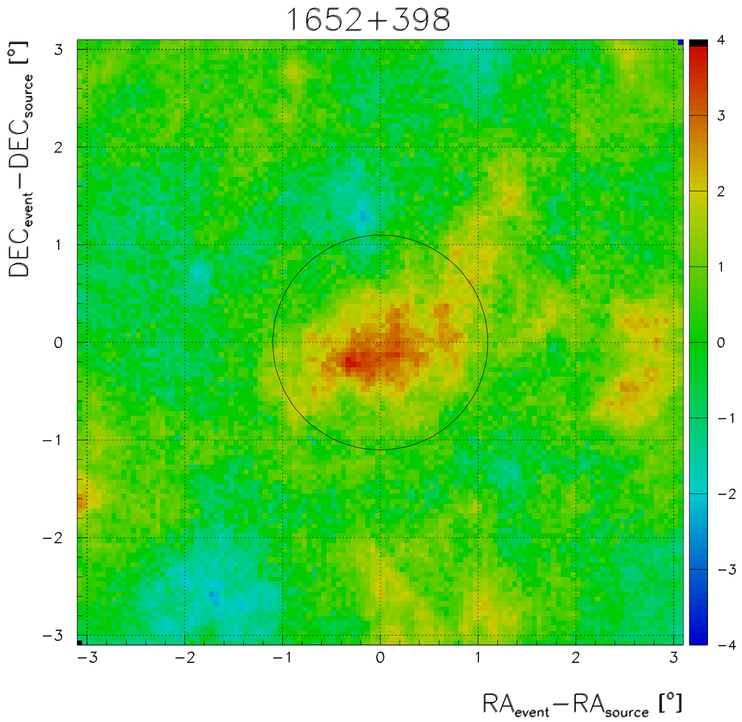

Figure 3. Significance in the vicinity of Mrk 501 (preliminary). The significance is calculated for a 1.1° circular source bin, thus neighboring bins are highly correlated.

the median of the distribution of angular differences between reconstructed and true shower direction for simulated events. The resolution function deviates considerably from a Gaussian shape, and this has important consequences for the optimal bin size in point source searches. Figure 2 (b) shows the sensitivity for point sources as a function of the source bin radius. Between 0.8° and 1.5°, the sensitivity function plateaus and depends only weakly on the chosen source bin radius.

The Milagrito detector has been operated with a minimum requirement of 100 hit tubes per event. As the effective area is not confined to the geometric area, the energy distribution of γ-showers (spectral index $\alpha = -2.4$) fulfilling the trigger condition is rather broad (see Figure 2 (c)), starting at energies as low as ~ 100 GeV. As it depends on the zenith angle, the median energy varies slightly with the source declination δ, ranging from ~ 3 TeV for sources at $\delta = 40°$ to 7 TeV for sources with $|\delta - \lambda| \simeq 20°$, where λ is the latitude of the detector.

4. Analysis Results

Standard analysis techniques are used for the point source search. Following Figure 2 (b), a source bin size with radius 1.1° is chosen. The source bin contains 48 % of the source events. To reduce the tail of showers with poor angular resolution, a minimum number of 40 tubes in the shower plane fit is required.

As the background rate is several orders of magnitude larger than the γ-ray rate

source	N_{on}	N_{bg}	sign. [σ]
0310+4104	1 093 565	1 091 776	1.9
0430+052	450 660	449 877	1.0
0554+5328	1 011 422	1 011 127	0.3
1101+384	1 136 929	1 137 912	-1.2
1133+704	643 958	643 028	1.0
1652+398	1 117 135	1 113 922	3.0
1727+502	1 056 895	1 057 574	-1.2
1807+698	640 099	640 153	-0.1
1959+650	761 785	760 713	1.5
2321+419	1 104 166	1 105 262	-1.7
2344+513	1 029 867	1 029 358	0.5

Table 2. Number of events in the source bin, estimated background, and significance for the 11 blazars. Results are preliminary.

from known point sources, it is necessary to estimate the hadronic background. We chose a procedure that accounts for the dependence of the detector efficiency on local coordinates, and the time dependence of the event rate [27]. For each event, background events are generated by calculating a new right ascension based on the local coordinates (zenith angle θ and azimuth angle ϕ) of the current event and event times of another event from a pool of typically one hour of data. This procedure is repeated 10 times for each event to decrease the statistical error on the background estimate. The significance of an excess or deficit is calculated using the method of Li and Ma [28].

A preliminary analysis reveals that none of the 11 analyzed blazars shows an excess which is statistically significant given the systematic uncertainties. The 99 % confidence level upper limit derived from the ~ 1 year of Milagrito data taking is of the order of $10^{-11}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Only Mrk 501 shows an excess $\sim 3\,\sigma$ at the source position, integrated over ~ 370 days of observation. Figure 3 shows the significance as a function of right ascension and declination in a $6^\circ \times 6^\circ$ region with the Mrk 501 position in the center. For each bin, the significance is calculated for the area of the circle with radius 1.1° and the bin center as the central point, thus neighboring bins are highly correlated.

We interpret the observation of the excess events as a confirmation of Mrk 501 as a TeV source. The measured excess rate of $(8.7 \pm 3.0)\,\mathrm{day}^{-1}$ is in agreement with the predicted rate of $(13 \pm 4)\,\mathrm{day}^{-1}$ using the Whipple flux given in Equation 2. Further analysis of the excess is still ongoing and requires a better understanding of Milagrito's sensitivity. At this point, sensitivity predictions are solely based on simulations. The detection of a steady standard candle and the subsequent detailed analysis of differences between simulation and data is needed. Unfortunately, ~ 350 days of observation with Milagrito was not enough to observe a signal from the Crab nebula.

For the full Milagro detector, simulations indicate that the Crab will be established at the $5\,\sigma$ level in one year of operation. While the detection of a TeV source with a ground-based wide-aperture instrument is a breakthrough in itself, the thorough analysis of a source will subsequently make the fine-tuning of analysis techniques, γ/hadron separation, and the detector simulation possible.

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