A SURVEY OF THE NORTHERN SKY FOR TeV POINT SOURCES

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ABSTRACT

A search for steady TeV point sources anywhere in the northern sky has been made with data from the Milagrito air-shower particle detector. Over 3×10^9 events, collected from 1997 February to 1998 May, have been used in this study. No statistically significant excess above the background from the isotropic flux of cosmic rays was found for any direction of the sky with declination between $-5°$ and $71°.7$. Upper limits are derived for the photon flux above 1 TeV from any steady point source in the northern sky.

Subject headings: gamma rays: observations — surveys

1. INTRODUCTION

Many objects in the universe emit electromagnetic radiation via thermal processes. High-energy gamma rays can only be produced in nonthermal, energetic acceleration processes, or by more exotic phenomena such as evaporating primordial black holes, topological defects, and neutralino annihilation. Observations of high-energy gamma rays have begun to reveal a picture of high-energy acceleration processes in the universe. Several reviews of high-energy gamma-ray astronomy have recently appeared (Ong 1998; Hoffman et al. 1999; Weekes 2000).

Cosmic gamma rays in the GeV regime can be detected directly with satellite-based detectors. The EGRET instrument (Thompson et al. 1993) surveyed the sky above 100 MeV and detected diffuse Galactic and extragalactic emission, five pulsars, at least 66 blazars (flat-spectrum radio quasars and BL Lacertae objects), and about 170 "unidentified" objects found along the Galactic plane (Thompson et al. 1995; Hartman et al. 1999). Many of the blazars exhibit time variability, while the pulsars seem to be steady, with no pulsed emission detected. The unidentified Galactic sources appear to be of two classes: relatively faint mid-latitude sources that may be associated with the Gould belt, and brighter low-latitude sources that may be Galactic pulsars or supernova remnants (Gehrels et al. 2000). A catalog of sources above 1 GeV contains 57 sources, including 10 that were not identified in the lower-energy catalogs (Lamb & Macomb 1997). This catalog includes the five pulsars and 21 blazars seen at lower energies, as well as 30 unidentified sources near the Galactic plane. The sensitivity of EGRET decreases at higher energies, making variability difficult to detect.

Gamma-ray fluxes fall rapidly with increasing energy, and the small size of satellite-based detectors limits the maximum energy at which sources can be detected. Observations with EGRET extended up to ~ 100 GeV, while the Gamma-Ray Large Area Space Telescope (GLAST; Gehrels & Michelson 1999) aims to detect bright sources up to ~ 300 GeV. Ground-based detectors have much larger collection areas, and have detected sources above 250 GeV. A high-energy gamma ray interacts high in the earth's atmosphere, producing an extensive air shower (EAS). Ground-based gamma-ray telescopes detect the products of EASs that survive to ground level.

Imaging atmospheric Cerenkov telescopes (ACTs) have been successfully employed over the last decade in the energy region from ~ 250 GeV to 50 TeV. ACTs detect Cerenkov light produced in the atmosphere by the ultrarelativistic charged particles in EASs. ACTs have detected emission from a number of sources, including three pulsar-driven nebulae (the Crab, Vela, and PSR 1706-44), and three blazars (Mrk 421, Mrk 501, and 1ES 2344+514). The TeV emission from the pulsar-driven nebulae appears to be steady, while the blazars exhibit strong flares. However, because of their small field of view (~ 10 msr) and low duty factor (typically 10%), ACTs are not well suited to scan the sky for TeV sources. In fact, only a small fraction of the sky has been examined with imaging ACTs. A survey of the northern sky using a nonimaging ACT has been reported (Helmken, Horine, & Weekes 1979; Weekes, Helmken, & L'Heureux 1979). Ong (1998), Hoffman et al. (1999), and Weekes (2000) give reviews of the ACT technique and observations.

Extensive air-shower particle detector arrays (EAS arrays) have been widely used to search for gamma-ray sources above ~ 50 TeV. An EAS array has typically consisted of a sparse array of scintillation counters that detects a small fraction of the charged EAS particles that reach ground level. An EAS array can operate 24 hr per day, regardless of weather, and can simultaneously observe the entire overhead sky; an EAS array is able to observe every source in its field of view every day of the year. No convincing evidence for steady gamma-ray emission above 50 TeV has been obtained with these detectors (Alexandreas et al. 1991; McKay et al. 1993).

We report here on the results of a systematic search of the northern sky for steady point sources of TeV emission, using data from the Milagrito detector, an EAS array sensitive to gamma rays in the 1 TeV region.

2. THE MILAGRITO DETECTOR

The Milagrito detector (Atkins et al. 2000), which operated from 1997 February to 1998 May, was the first EAS array to use a large volume of water as the detection medium. Milagrito used photomultiplier tubes (PMTs) deployed under water to detect the Cerenkov radiation produced in the water by relativistic, charged EAS particles. Most of the shower particles (including the gamma rays, which produce electrons and positrons via pair production) falling within the area of the water can be detected with this technique. Milagrito had good sensitivity to primary gamma rays around 1 TeV, while maintaining the large-aperture and high-duty-factor attributes of an EAS array. Milagrito had a rather broad energy response with no well-defined energy threshold. The median energy for detected photons was ~ 3 TeV for a source at declination $40°$, rising to ~ 7 TeV for sources at declinations of $20°$ and $60°$.

Milagrito utilized 228 8"-diameter PMTs located in a plane on a 2.8×2.8 m grid near the bottom of a large, covered pond of water. Data were taken with 1, 1.5, and 2 m of water above the PMTs. The pond is located at an altitude of 2650 m above sea level (atmospheric overburden = 750 g cm^{-2}) in the Jemez mountains west of Los Alamos, New Mexico ($35°9$ north, $106°7$ west). As in a conventional EAS array, the direction of the primary gamma ray is reconstructed by measuring the relative times at which the individual PMTs were struck by light produced by particles in the shower front. To reduce the impact of stray light, only tubes registering pulses larger than two photoelectrons are used in the shower fits.

The angular resolution for cosmic-ray events was studied by comparing the incident directions separately reconstructed by two independent, interleaved portions of the detector. The resulting angular resolution is in good agreement with expectations from a detailed Monte Carlo simulation (Atkins et al. 2000). However, this comparison is not sensitive to certain systematic effects, such as those due to errors in the reconstructed shower core location. Observations of the cosmic ray shadow of the moon (Wascko et al. 1999) indicate that the simulation reproduces the actual detector point-spread function quite well. These observations are for events initiated by cosmic rays, and it is the point-spread function for events initiated by gamma rays that must be known in order to optimize the search for a point source of gamma rays. The simulations indicate that the angular resolution is 10%–20% better for gamma-ray events. This is in general agreement with the shape of the

signal from Mrk 501, observed with Milagrito (Atkins et al. 1999). The technique used to search for point-source emission, described below, depends only weakly on the detailed shape of the detector point-spread function. Further details on Milagrito are available in Atkins et al. (1999).

3. ALL-SKY SURVEY TECHNIQUE

Milagrito had no ability to distinguish showers initiated by gamma rays from background showers initiated by charged cosmic rays. Because of the large number of isotropic background cosmic-ray showers, a strong gamma-ray point source would appear as an excess number of showers coming from a small region of the sky, consistent with the Milagrito point-spread function. The point-spread function has wider tails than a Gaussian distribution, and narrows rapidly with increasing value of $N_{\rm fit}$, where $N_{\rm fit}$ is the number of PMTs participating in the fit to the shower plane. This analysis requires $N_{\rm fit} > 50$, a tighter cut than was used in Atkins et al. (1999), since this reduces the amount of data to be handled without significantly decreasing the sensitivity to point sources. For events with $N_{\rm fit} > 50$, the median value of the angular resolution is $\sim 1°$. This analysis uses 3.4×10^9 events.

The method used involves dividing the sky into bins, and examining each bin for an excess number of events. Rectangular sky bins rather than circular bins are used because they can be easily configured to cover the entire search region. With the $N_{\rm fit} > 50$ cut, the optimal bin on the sky in which to search for a point source is $\sim 2° \times 2°$. The actual bin size in celestial coordinates is $2°22$ (declination, δ) $\times 2°22/\cos \delta$ (right ascension, α), with one abnormally sized bin (at each δ) ending at $\alpha = 360°$. Because the expected significance for a source depends only weakly on small changes of the bin size (Atkins et al. 1999), a bin a little larger than optimal was chosen to reduce the number of bins in the survey. A map consisting of a grid of 4319 bins covered the sky from $\delta = -3°9$ to $71°7$. An unknown source may be located near the edge of a bin. In this case, the significance of a source, expressed in terms of the number of standard deviations above background, would be $\sim 60\%$ of the significance of a source located at the center of the bin. Thus, three additional maps were also examined: one with bins shifted by $1°11$ in δ, one with bins shifted by $1°11/\cos \delta$ in α, and one with bins shifted by these amounts in both δ and α. With this procedure, the largest loss in significance due to the location of a source relative to the center of a bin is $\sim 15\%$. The survey with four maps covers the region from $\delta = -5°$ to $71°7$.

An accurate estimate of the expected background is needed for each bin. The expected background in a given bin depends on its exposure and on the detector efficiency, which varies with the local coordinates (δ, and hour angle, H.A.). The background estimation in each bin is determined using the data themselves (Alexandreas et al. 1991, 1993). Random "background" events are generated for each observed event by associating the event local coordinates (δ, H.A.) with times selected randomly from all event times recorded over a 2 hr period. New values of celestial coordinates are then calculated for each background event. Because the selection of a new event time amounts to a rotation of the celestial sphere with respect to the earth, this method changes only the α of an event, but not its δ. Fifteen background events are generated for each actual event so that the statistical error for the estimated background is

small compared to the fluctuations in the signal map. The background events are then binned in the same manner as the data events: the expected background level is the number of background events falling into a source bin, divided by 15. It has been shown that this method produces background events that track changes in the trigger rate and are free of systematic errors (Alexandreas et al. 1991, 1993). Once signal and background maps have been produced, they are compared on a bin-by-bin basis, and the statistical significance of the observed number of events being due to a fluctuation of the expected background is calculated using the method of Li & Ma (1983).

4. RESULTS

Figure 1a shows the distribution of the statistical significance of the observed number of events above the expected cosmic-ray background for each of the 4319 independent bins of the first map. None of these bins shows a significant excess (or deficit), considering the number of independent bins examined. The distributions for the shifted maps are shown in Figures 1b–1d. The bins in a given map are independent of each other, but they are not independent of the bins in the other maps. A Monte Carlo study indicates that the effective number of independent bins searched, for

a large excess to appear in any bin of the four maps is $\approx 2.5 \times 4319 \approx 10,800$. The largest observed excess is 3.9 σ, corresponding to a post-trials probability of $\sim 50\%$ of being due to a fluctuation of the background. Thus, no strong, steady source of TeV emission is observed in the northern sky for the period from 1997 February to 1998 May.

The sensitivity of Milagrito has been evaluated using the Monte Carlo simulation (Atkins et al. 2000). This has been verified by comparing the observed rate of gamma rays from Mrk 501 from 1997 February to October (Atkins et al. 1999), with the flux measured by air Cerenkov telescopes (Samuelson et al. 1998; Aharonian et al. 1999), and by comparing the observed rate of cosmic-ray events with the expected event rate, given the measured fluxes reported in Asakimori et al. (1998), and Wiebel-Sooth, Biermann, & Meyer (1998): the rates in these comparisons agree to within 10% (Atkins et al. 1999). While the close agreement of these rates may be partially fortuitous, it can be used to limit the systematic error on the energy scale to less than 30%. A direct measurement of the energy scale using the deflection of the observed shadow of the moon in the geomagnetic field implies that the error in the energy scale is less than ±85% (M. Wascko et al., in preparation).
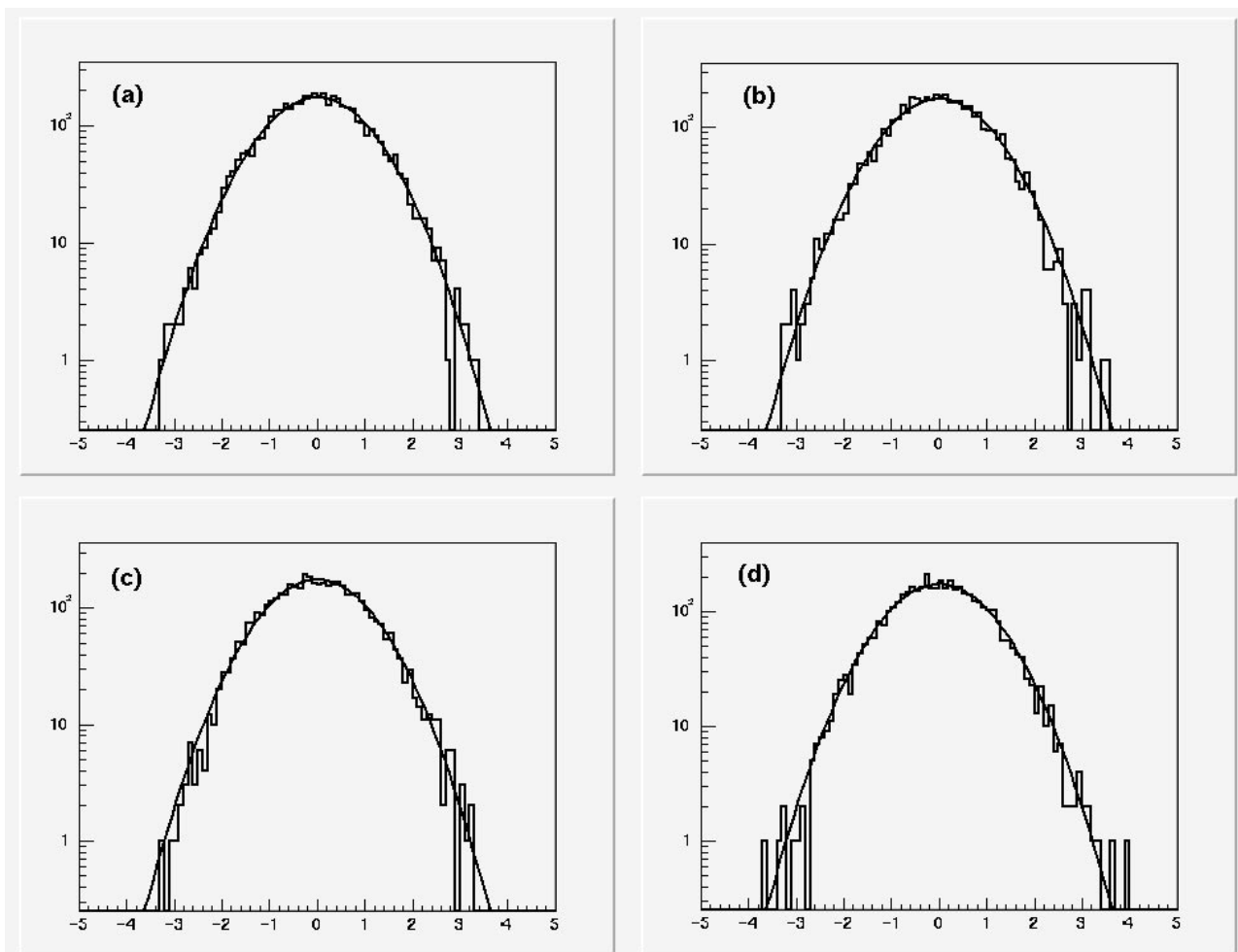

FIG. 1.—(a) Statistical significance for the observed number of events above the expected cosmic-ray background for each of the 4319 independent bins of the first sky map. The smooth curve is a Gaussian with unit width and area equal to 4319. (b)–(d) Statistical significance for the bins of the three shifted maps.

The upper limit on the number of gamma-ray events in a bin varies according to the number of observed events in that bin. Rather than give gamma-ray flux upper limits on a bin-by-bin basis, we give upper limits for a typical bin, as a function of declination. The upper limit on the flux from a source, Φ_γ, at a given declination, expressed in terms of the upper limit on the number of gamma-ray events, N_γ, for the source bin at that declination, is

$$N_\gamma = \int \Phi_\gamma(E) A_{\mathrm{eff}}(E, \delta, \mathrm{H.A.}(t)) \varepsilon \, dE \, dt \, , \qquad (1)$$

where $A_{\mathrm{eff}}(E, \delta, \mathrm{H.A.})$ is the effective area of Milagrito as a function of gamma-ray energy and the local coordinates of the source position, H.A.(t) is the hour angle of the source as a function of time, and ε is the fraction of events from a source that falls within the source bin. The time integral is taken over the experiment observation time. Assuming that an integral source spectrum is $\propto E^{-1.5}$, the resulting typical 90% confidence level upper limit on the integral gamma-ray flux above 1 TeV for any steady source as a function of declination is shown in Figure 2. For comparison, the integral gamma-ray flux above 1 TeV from the Crab, measured by the Whipple collaboration (Hillas et al. 1998), is also shown in Figure 2.
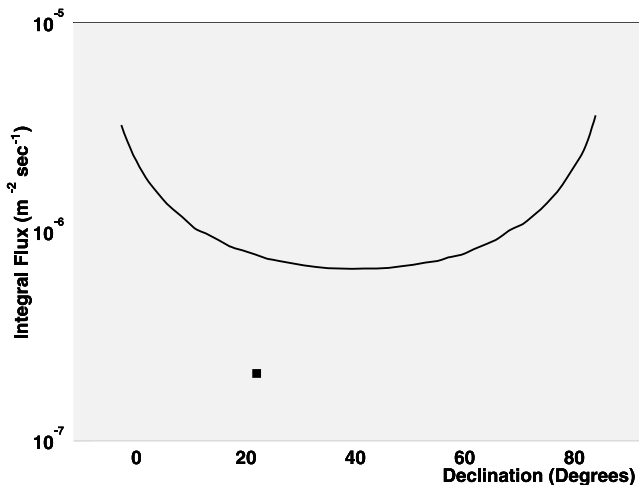

FIG. 2.—Typical 90% confidence level upper limit on the integral flux above 1 TeV for a steady source as a function of declination (δ), assuming an integral flux $\propto E^{-1.5}$. The square shows the measured integral flux above 1 TeV from the Crab from Hillas (1998) for comparison.

We have also searched for steady emission from the four known northern TeV sources, the Crab, Mrk 421, Mrk 501, and 1ES 2344 + 514. In each case, the bin in any of the maps that is most nearly centered on the actual source position was used. The results are shown in Table 1. Because no bin is exactly centered on the source positions, and the bins used in this analysis are larger than the optimal bin, a small loss of sensitivity is to be expected. The observed excess for the Crab (1.1 σ) is in good agreement with the expected signal size (1.3 σ), considering the expected 7% loss of sensitivity. The excess from Mrk 501 (2.8 σ) is less than reported in Atkins et al. (1999) (3.7 σ). This is partially due to the small expected loss in sensitivity discussed above (an expected loss of $\sim 12\%$), and partially due to statistical fluctuations in the number of events passing the tighter N_{fit} cut, and in the signal size in the larger bin used here.

5. CONCLUSIONS AND OUTLOOK

A systematic survey of the northern sky ($-5° < \delta < 72°$) for point TeV sources has been made with data from the Milagrito air shower detector. No source with a steady flux larger than ~ 5 times the gamma-ray flux above 1 TeV from the Crab has been observed for the period from 1997 February to 1998 May. A paper describing a search of the northern sky for episodic emission on a variety of timescales, using data from Milagrito, is in preparation.

Milagrito was dismantled in 1998 to install the Milagro detector. Milagro began data taking in 1999 December. Milagro has ~ 4 times better sensitivity than Milagrito, because of its larger size, and the ability to distinguish photon-initiated showers from background showers using a second layer of PMTs located under 6 m of water. In addition, each photomultiplier tube in Milagro has a reflecting conical baffle to increase its light-collection area, and to eliminate late signals due to horizontally traveling light. The energy response of Milagro is similar to that of Milagrito. An array of 175 4.5 m² water detectors is being installed over an area of 10,000 m² surrounding the pond, which should improve the sensitivity of Milagro by a further factor of 2. One of the goals of Milagro is to sensitively survey the northern sky for TeV gamma-ray sources over a wide variety of timescales.

TABLE 1

OBSERVATIONS WITH MILAGRITO OF THE FOUR KNOWN NORTHERN TeV SOURCES.

Source	α (deg)	δ (deg)	$\Delta(\alpha)$ (deg)	$\Delta(\delta)$ (deg)	On-Source Events	Excess Events	Significance (σ)
Crab	83.6	22.0	−0.02	0.33	9.15×10^5	1050	1.1
Mrk 421	166.1	38.2	0.51	−0.13	1.13×10^6	−850	−0.8
Mrk 501	253.5	39.8	0.40	0.31	1.15×10^6	2980	2.8
1ES 2344 + 514	356.2	51.4	0.04	−0.24	1.06×10^6	227	0.2

NOTE.—$\Delta(\alpha)$ and $\Delta(\delta)$ are the angular distance from the center of the examined bin to the actual source location in right ascension and declination, respectively. "On-source events" is the number of observed events in the source bin, and "Excess events" is the difference between the number of observed events and the estimated number of background events in that bin.

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