Proceedings of ICRC 2001: 1 © Copernicus Gesellschaft 2001

ICRC 2001

A Search for TeV Gamma-Ray Emission from Selected AGN Using Milagro

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Abstract. The Milagro gamma-ray observatory, located near Los Alamos, NM, employs a water-Cherenkov technique to continuously monitor the northern sky for astrophysical gamma-ray emission near 1 TeV. Milagro's high duty-cycle (∼95%) and wide aperture (∼2 sr) allows for the detection of flaring behavior associated with TeV AGN, even during daytime transits. Results are presented from a search of the Milagro 2000-2001 data set for TeV emission from selected AGN, including the bright flare of Mrk421 in early 2001.

1 Introduction

The Milagro water-Cherenkov detector (60 x 80 x 8 m^3) is an all-sky monitor sensitive to the extensive air showers (EAS) produced by gamma rays incident on the atmosphere in the energy range 200 GeV to 20 TeV. Milagro, which operates at 2630 m above sea level, employs two layers of submerged photomultiplier tubes (PMTs) to detect the Cherenkov light produced by secondary particles entering the covered reservoir of water. The first layer, consisting of 450 PMTs on a 2.8 x 2.8 m^2 grid under 1.5 m of purified water, utilizes the relative arrival time of the Cherenkov photons at the PMTs to reconstruct the direction of the incoming EAS with an accuracy of ~ 0.75 degrees. The second layer of 273 PMTs located at ∼6 m depth is used to identify penetrating particles such as muons, hadrons and very energetic electromagnetic particles. Due to the low cross section for photo-production of hadrons, one expects many more muons and hadrons at ground level in an EAS initiated by a hadronic cosmic ray, allowing this second layer to be useful for determining the species of the primary particle. This is crucial for the detection of TeV sources, as the EAS initiated by hadronic cosmic rays greatly outnumber (∼10,000:1) those initiated by gamma rays. A rejection technique for Milagro, making use of this second layer has been developed, and is detailed in Sinnis *et al.* (2001). This technique has led to the detection of the Crab Nebula with a significance of 4.8σ for the entire Milagro data set and confirms that the detector is performing as expected. A more detailed description of Milagro can be found in these proceedings (Sullivan *et al.*, 2001).

Milagro's ability to continuously monitor all sources in the overhead sky, even during daytime transits, makes it well suited for studies of AGN, which are known to be highly variable and exhibit flaring behavior. A smaller, less sensitive version of Milagro, known as Milagrito, detected the bright flare of Mrk 501 in 1997 (Atkins *et al.*, 1999). The improved sensitivity of Milagro, due to its larger effective area and the ability to reject some of the cosmic-ray background, enables it to observe similar phenomena with appreciable significance.

2 AGN Sample

Twenty-six AGN within the field of view of Milagro (0 < dec < 70) were selected for continuous observation. Only relatively nearby (z<.1) AGN are studied in order to minimize the attenuation of any potential signal by extragalactic background photons. This sample includes 3 AGN already detect-

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Nominal Coordinates	Name	Class	z
1101+384	Mrk 421	XBL	0.031
1652+398	Mrk 501	XBL	0.034
2344+514	1ES	XBL	0.044
0033+595	1ES	XBL	0.086
0110+418	RGB	XBL	0.096
0152+017	RGB	XBL	0.080
0153+712	RGB	XBL	0.022
0214+517	RGB	XBL	0.049
0314+247	RGB	XBL	0.054
0656+426	RGB	XBL	0.059
1133+704	Mrk 180	XBL	0.046
1532+302	RGB	XBL	0.064
1610+671	RGB	XBL	0.067
1727+502	I Zw 187	XBL	0.055
1741+196	1ES	XBL	0.083
1959+650	1ES	XBL	0.048
2321+419	1ES	XBL	0.059
2322+346	RGB	XBL	0.098
0010+106	III Zw 2	FSRQ	0.090
0138+398	B2	FSRQ	0.080
0321+33	B2	FSRQ	0.062
1413+436	RGB	FSRQ	0.090
2209+184	PG	FSRQ	0.070
1219+285	W Comae	RBL	0.102
1807+698	3C371	RBL	0.051
2200+420	BL Lac	RBL	0.069

Table 1. This table lists 26 AGN to be studied by Milagro. Results will be presented at the conference for the excesses detected from these sources

ed at TeV energies: Mrk 421 (Punch *et al.*, 1992), Mrk 501 (Quinn *et al.*, 1996), 1ES2344+514 (Catanese *et al.*, 1998). In addition 15 other x-ray selected BL Lacs, and 5 FSRQ's as motivated in Perlman (1999), as well as 3 radio-selected BL Lacs detected by the EGRET instrument (Mukherjee *et al.*, 1997), are included. The coordinates, common names, and redshifts of these AGN are listed in Table 1. As it has become the standard reference of TeV gamma-ray astronomy, the Crab Nebula is also studied for evaluation purposes.

3 Event Reconstruction

Every event satisfying the trigger condition for Milagro is reconstructed to determine its characteristics. These traits include the incident direction of the shower plane, the core location, and the nature (hadronic or electromagnetic) of the shower. The first step in reconstructing an event is to determine the location of the shower core. After the core is located, a correction, 0.07 ns for every meter a hit PMT is distant from the core, is applied to account the curvature of the shower front. A sampling correction is then applied. This correction accounts for the effect that on average, the larger the pulse height detected by a PMT, the earlier the measured arrival time, and is due to the shower plane having a thickness. After these corrections are performed, the incident direction of the shower plane is determined by a weighted least squares (χ^2) fit. The χ^2 is minimized with respect to the arrival time of the shower plane, and two directional cosines. This fitting procedure is iterative in that after a fit is performed, PMTs with a large contribution to the χ^2 are removed, and the plane is fit again. This process continues until the result converges. A consequence of this is a strong dependence of the angular resolution on the number of PMTs participating in the fit (nFit). Approximately 97% of the events which trigger Milagro are fit successfully by this method with an average angular resolution of ~ 0.75 degrees. More details concerning the corrections and fitting process are published in Atkins *et al.* (2000). Finally, after the direction is determined, a parameter related to the nature of the primary particle is calculated to perform background rejection. An explanation of this parameter known as compactness, or C, as well as the effectiveness of this technique can be found in Sinnis *et al.* (2001).

Due to the high rate and large size of the raw data in Milagro, the event reconstruction must be performed online. For most events, only the processed data is saved to tape. However, raw data for events initially reconstructed in the vicinity of certain sources, such as the Crab Nebula, are saved to tape. As the event reconstruction for Milagro is continually evolving, this allows for the re-reconstruction of the data with new algorithms. This newer version of the processed data can then be compared to the previous version to test the effectiveness of the new methods, as well as to determine an improved significance of detection. Upon receiving notice that Mrk 421 was flaring on January 17, 2001, Milagro began saving raw data from the surrounding region.

4 Analysis

The analysis for Milagro consists of looking for an excess of events above the cosmic-ray background in any given direction. Background maps are generated from the actual data using the method described in Alexandreas *et al.* (1993). More specific discussion of the technique utilized is found in Atkins *et al.* (1999). Data from the signal and background maps are placed into overlapping circular bins. The optimal binsize, related to the point spread function, is 1.2 degrees radius. In addition, only events with nFit > 20 are used. This cut is performed to eliminate poorly reconstructed showers. Finally, a cut keeping events with compactness parameter, C > 2.5, is applied to the data to perform background rejection. The expected significance is optimized by utilizing these values, although the maximum is sufficiently flat in these parameters that exact values are not important. The significance of the signal excess over background is determined by the method of Li and Ma (Li & Ma, 1983). A search for appreciable excess in the direction of the 26 AGN is performed for the length of the entire analyzed data set, as well as for 1, 3, 5, 7, 10, 14, 21, and 30 day timescales.

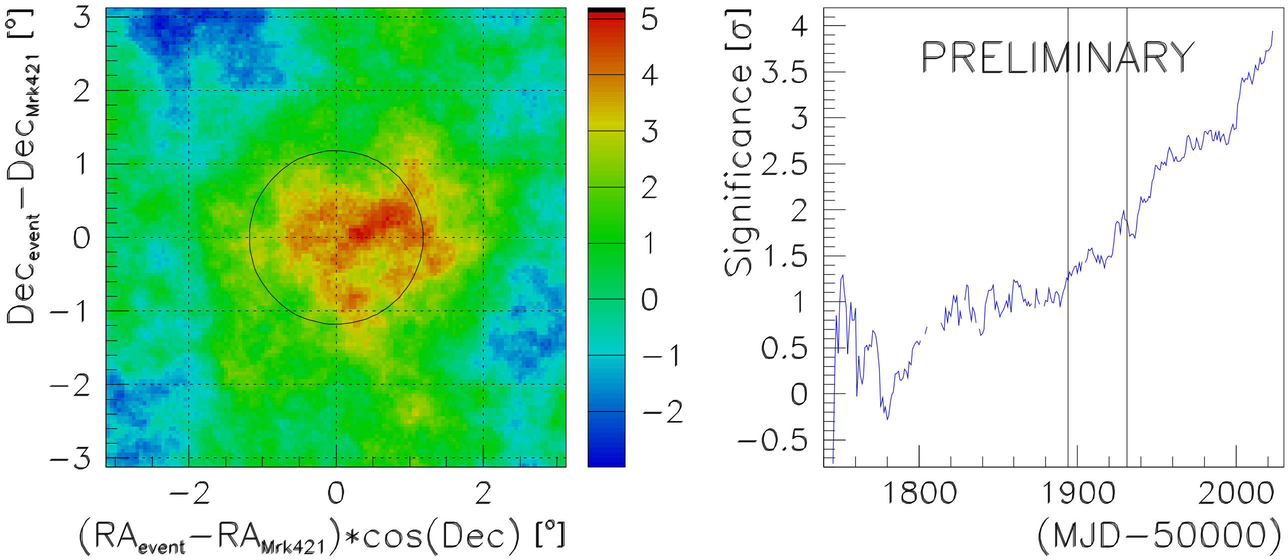

Fig. 1. On the left, a preliminary sky map of region centered on Mrk 421 for the period: June 14, 2000, to April 24, 2001. Neighboring points are highly correlated due to overlapping bins. The circle represents the bin size used for the analysis and is centered on the true position of Mrk 421. On the right, a preliminary plot of the accumulated Mrk 421 signal *vs.* time. The leftmost vertical line represents the date when the improved core reconstruction algorithm was implemented. The rightmost vertical line reresents the date the new calibrations were implemented. The date 1910 corresponds to January 1, 2001.

5 Data Set

Milagro began acquiring data in engineering mode on June 8, 1999, and has operated nearly continuously since January, 2000. As the understanding of the detector has increased, the online event reconstruction has undergone many changes. While many of these modifications are relatively minor, two of these have resulted in large increases in the detector's sensitivity. The first, occurring on June 14, 2000, involved implementing the background rejection algorithm online. Monte Carlo simulations indicate that this should result in an increase in sensitivity by a factor (Q factor) of 1.8(Sinnis *et al.*, 2001). A new core reconstruction algortitm, implemented on December 15, 2000, constitutes the second major change. Monte Carlo simulations show that this change should result in an additional Q factor of 1.4. In addition, recent studies have improved the pulse height calibration of Milagro. These improvements affect both the hadron rejection and to a lesser extent the angular reconstruction of Milagro. More details can be found in Sinnis *et al.* (2001). Unfortunately, only limited raw data exists for events initially reconstructed in the vicinity of the candidate blazars. This does not allow for re-reconstruction of the data with the improved calibrations. However, as previously discussed raw data exists for events initially reconstructed in the vicinity of Mrk 421 during the time interval beginning January 17, 2001, to present. This data was reprocessed with the new calibrations, and is utilized in the analysis of Mrk 421. A consequence of these upgrades is that one must combine data utilizing varying calibrations and reconstruction techniques to study the AGN over larger time periods.

Milagro has detected the Crab Nebula with high significance by making use of the background rejection technique. Therefore, the Milagro data set from June 14, 2000, when the compactness parameter became part of the processed data, until April 24, 2001, was searched for TeV emission from the candidate blazars. This interval consists of 278 source transits. However, due to downtime for repairs and power outages, the effective exposure is actually 264 days. This time period includes the large flare of Mrk 421 in early 2001, as reported by HEGRA, Whipple and the RXTE All-Sky Monitor. The overall sample consists of XX.XXX billion events satisfying a trigger condition of at least ~ 50 top layer tubes hit within a window of 200 ns, taken at an average trigger rate between 1500 and 2000 Hz.

6 Results

6.1 Mrk 421

For the analyzed data set, Milagro detects an excess of 3337 ± 846 events from Mrk 421, corresponding to 4.0σ. The combined analysis cuts keep 11% of the events in the source bin. The left plot in Figure 1 is a sky map of detected significance for the region surrounding Mrk 421. Neighboring points on this map are highly correlated as the bins are overlapping. The right plot in Figure 1 shows how the significance at the position of Mrk 421 was accumulated. This preliminary result is consistent with expectations, and indicates that Milagro has detected Mrk 421 as a source of TeV gamma rays. The average rate of excess events observed is 12.6 ± 3.2 day^{-1}. Figure 2 shows the excess at the position on Mrk 421 divided by background for time interval studied. The data are binned in 30 day intervals, with the first and last points on the plot containing only 4 days each.

For comparison purposes, Milagro sees an excess from the Crab of 2134 ± 698 events, or 3.1σ during this time period. This is consistent with expectations and indicates that Mrk 421 produced an average flux level higher than the Crab for this data set. As expected, no flaring activity was detected for the Crab.

Results will be presented at the conference from the search for shorter timescale emission at Mrk 421's position.

6.2 Other AGN

Results will also be presented at the conference from the search for significant excess from the 25 other blazars for the entire time interval, as well as results from the short-term flare search.

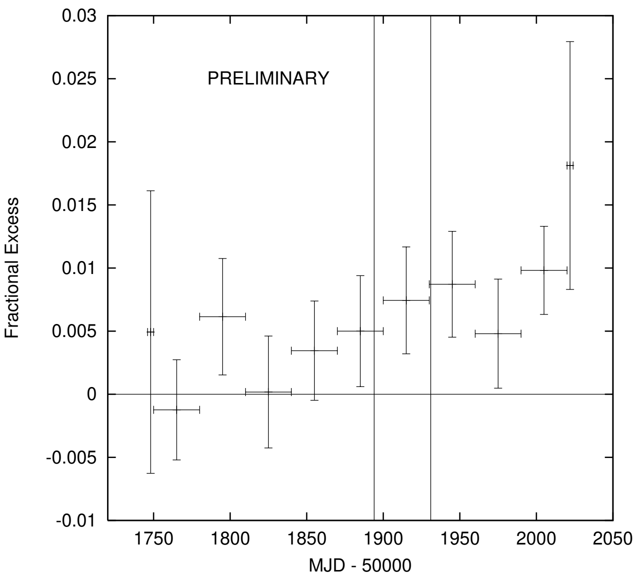

Fig. 2. Preliminary fractional excess *vs.* time from Mrk 421 as seen by Milagro. The leftmost vertical line represents the date when the improved core reconstruction algorithm was implemented. The rightmost vertical line reresents the date the new calibrations were implemented. The data are binned in 30 day intervals, with the first and last points containing only 4 days each. The date 1910 corresponds to January 1, 2001.

7 Conclusions

Milagro has detected Mrk 421 during its bright flare in early 2001. This, coupled with the detector's ability to monitor AGN during daytime transits, when observations with Air Cherekov Telescopes are impossible, shows that the Milagro gamma-ray observatory is poised to make significant contributions to the field of TeV astrophysics. The analysis of the signal from Mrk 421 is still ongoing. Thus, the results presented in this paper are preliminary. Updated results, including the short-term flare search, will be presented at the conference for Mrk 421 and the other 25 AGN.

Acknowledgements. This research was supported in part by the National Science Foundation (Grant Numbers PHY-9722617, -9901496, -0070927, -0070933, -0070968, -0096256), the U. S. Department of Energy Office of High Energy Physics, the U. S. Department of Energy Office of Nuclear Physics, Los Alamos National Laboratory, the LDRD program at LANL, the University of California, the Institute of Geophysics and Planetary Physics, The Research Corporation, and the California Space Institute. We would also like to recognize the hard work of Scott Delay and Michael Schneider, whose dedication has been instrumental in operating Milagro. The author would also like to thank the American Astronomical Society for providing funding to attend this conference.

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