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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 Čerenkov technique to continuously monitor the northern sky for astrophysical gamma-ray emission near 1 TeV. Milagro's high duty-cycle ($\sim$95%) and wide aperture ($\sim$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 January 2001.

1 Introduction

The Milagro water-Čerenkov 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 2650 m above sea level, employs two layers of submerged photomultiplier tubes (PMTs) to detect the Čerenkov light produced by secondary particles entering the covered reservoir of water. The first layer, consisting of 450 PMTs on a 3 x 3 m^2 grid under 1.5 m of purified water, utilizes the relative arrival time of the Čerenkov photons at the PMTs to reconstruct the direction of the incoming EAS with an accuracy of $\sim$.75 degrees. The second layer of 273 PMTs located at $\sim$6 m depth is used to identify penetrating particles such as muons, hadrons and very energetic electromagnetic particles. Due to the low cross section for photo-production of hadrons, one expects many more muons and hadrons at ground level in a EAS initiated by a hadronic cosmic ray, allowing this second layer to be useful for determining the species of the primary particle. This is crucial for the detection of TeV sources, as the EAS initiated by hadronic cosmic rays greatly outnumber ($\sim$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, make it well suited for studies of AGN, which are known to be highly variable and exhibit large scale 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, clearly 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

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detected at TeV energies: Mrk 501, Mrk 421, 1ES2344+514. 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 candle of TeV gamma-ray astronomy, the Crab Nebula is also studied for evaluation purposes.

3 Data Set

The Milagro data set from December 15, 2000, to April 17, 2001, consisting of 122 source transits was searched for TeV emission from the candidate blazars. This time interval includes the large flare of Mrk 421 in early 2001, as reported by several Air Čerenkov Telescopes. The overall sample consists of 12.647 billion events satisfying a trigger condition of at least 50 top layer tubes hit within a window of 200 ns, taken at an average data rate of ∼1500 Hz.

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 time-sloshing method as described in Atkins et al. (2000). Data from the signal and background maps are placed into overlapping circular bins. Clearly, an optimal binsize exists that is related to the point spread function of Milagro. Analysis has determined the optimal binsize to be 1.2 degrees radius. In addition, since the angular resolution of the detector is dependent on the number of tubes participating in the fit (nFit), only events with nFit > 20 are used. Finally, a cut keeping events with compactness parameter, C > 2.5, is applied to the data to perform background rejection. An explanation of the parameter C, as well as the effectiveness of this technique can be found in Sinnis et al. (2001). The detected 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 sample data set, as well as for 1, 3, 5, 7, 10, 14, 21, and 30 transit timescales.

5 Results

For the entire sample data set, Milagro detects an excess of 2491 ± 540 events in the bin centered on the position of Mrk 421, corresponding to 4.6σ. 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 location of maximum excess, 5.6σ, is displaced to the southeast from the true position of Mrk 421 by total of $\sim .4$ degrees, indicating a possible pointing error in Milagro. Here and throughout this paper, east, west, etc., refers to the direction on the sky map, not to an actual direction on the celestial sphere.

Coordinates	Name	Class	z	Significance
1101+384	Mrk 421	XBL	0.031	4.6σ
1652+398	Mrk 501	XBL	0.034	-0.4σ
2344+514	1ES	XBL	0.044	0.7σ
0033+595	1ES	XBL	0.086	0.0σ
0110+418	RGB	XBL	0.096	0.0σ
0152+017	RGB	XBL	0.080	0.0σ
0153+712	RGB	XBL	0.022	0.0σ
0214+517	RGB	XBL	0.049	0.0σ
0314+247	RGB	XBL	0.054	-0.7σ
0656+426	RGB	XBL	0.059	0.3σ
1133+704	Mrk 180	XBL	0.046	0.0σ
1532+302	RGB	XBL	0.064	1.2σ
1610+671	RGB	XBL	0.067	0.0σ
1727+502	IZw 187	XBL	0.055	0.0σ
1741+196	1ES	XBL	0.083	0.0σ
1959+650	1ES	XBL	0.048	0.0σ
2321+419	1ES	XBL	0.059	0.0σ
2322+346	RGB	XBL	0.098	0.0σ
0010+106	III Zw 2	FSRQ	0.090	0.0σ
0138+398	B2	FSRQ	0.080	0.0σ
0321+33	B2	FSRQ	0.062	0.0σ
1413+436	RGB	FSRQ	0.090	0.0σ
2209+184	PG	FSRQ	0.070	0.0σ
2200+420	BL Lac	RBL	0.069	0.0σ
1219+285	W Comae	RBL	0.102	0.0σ
1807+698	3C371	RBL	0.051	0.0σ

Table 1. Preliminary Significance of excess(deficit) detected in bin centered on AGN position. A significance of 0.0 is the NULL entry, corresponding to not processed yet (should be finished by June 1).

The search for shorter timescale emission at Mrk 421's position yields excesses $> 3\sigma$ for intervals as short as 10 days. Although this is interesting, one must account for trials and eliminate correlations when searching the various timescales. This has not been performed on this data set due to issues with Milagro's calibration discussed later. Thus, one can not distinguish whether Milagro has detected brief flaring behavior, or a statistical fluctuation of the data from this information.

For comparison purposes, Milagro sees an excess from the Crab of 541 ± 464 events, or 1.2σ 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.

No significant excess was seen from any of the 25 other blazars for the entire time interval. Table 1 shows the significance detected by Milagro during this time period at the position of each of these blazars. Results will be presented at this conference for the short term flare search from the 26 AGN.

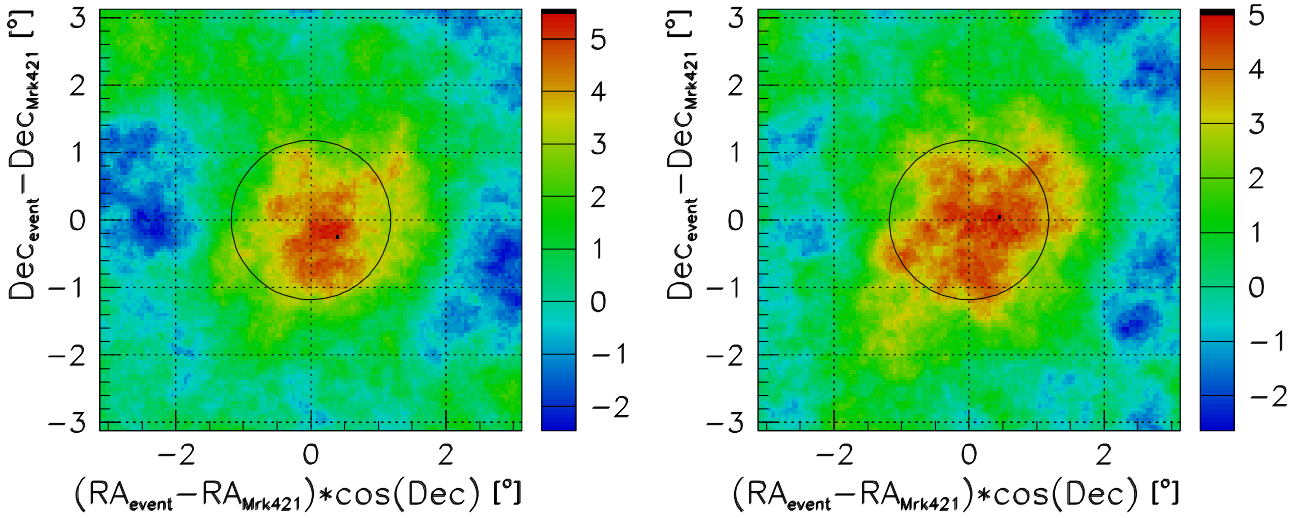

Fig. 1. Preliminary sky map of region centered on Mrk 421. Neighboring points are highly correlated due to overlapping bins. The circle represents the bin size used for the analysis. On the left are results utilizing only the old calibration, on the right results from the combined calibration sample.

6 Calibration Problem

Recent studies have indicated problems with the pulse height calibration of Milagro for the data set analyzed. These problems 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). While this is unfortunate, raw data exists for events initially reconstructed in the vicinity of Mrk 421 during the time interval between January 17, 2001, to April 24, 2001, consisting of 92 source transits. This data was reprocessed with the new calibrations. Unfortunately, only limited raw data exists for all 25 other AGN at all times, as well as for Mrk 421 prior January 17, 2001. This sample, while limited in scope, is large in size and does not allow for quick or efficient processing. Further, any future data will employ the improved calibrations, as they have been installed online. The consequence of this is that one must combine data utilizing both calibrations to study the AGN over larger time periods.

7 New Calibration Effects

Milagro sees an excess from Mrk 421 of 3.8σ with the improved calibrations during the 92 transit interval. The maximum significance of 4.8σ is located $\sim$ .2 degrees to the west of Mrk 421's position. Using the old calibrations for this same time period, Milagro detects a significance of 4.2σ, with a maximum of 4.7σ located $\sim .4$ degrees to the east of the location of Mrk 421. Clearly the improved calibrations affect the performance of Milagro. In order to determine a more accurate significance detected by Milagro during the entire time interval, one must combine data for the early part using the old calibrations with data from the latter portion reconstructed using the new calibrations. For the first data interval which utilizes the old calibrations, an excess of 2.2σ at the position of Mrk 421 is seen, with a maximum of 4.2σ located ~ 1.0 degrees to the east of the true location. Results from the combination of data sets, with differing calibrations are presented below.

8 Mrk 421

8.1 Overall Result

The right plot in figure 1 shows a sky map of the significance of excess over background in the region centered on Mrk421 for the combined data set. Again, neighboring points on this map are highly correlated as the bins are overlapping. The analysis cuts keep 9% of the events in the source bin. The excess at the Mrk421's position is 2687 ± 618 events, corresponding to 4.3σ. The maximum excess of 5.1σ is displaced to the east from the true position of Mrk 421 by $\sim .4$ degrees. Much of this displacement arises from the first part of the data set involving the old calibrations. It should be noted that the combined data set used here is slightly longer in duration than the original sample. The new interval consists of 7 more transits, or 129 total. This analysis is consistent with expectations, and indicates that Milagro has detected Mrk 421 as a source of TeV gamma rays during this time period. The average rate of excess events observed is 20.8 ± 4.8 day^{-1}.

8.2 Short Term Flare Search Result

The search for flares on the 8 aforementioned timescales yielded many results with significance $> 3\sigma$. Figure 2 shows a plot of rolling 30 transit significance for Mrk 421. Each date on the plot corresponds to the Modified Julian Date (MJD) which contained the bulk of the exposure to the transit. The

Timescale	$\sigma < -2$	$-2 \geq \sigma < -1$	$-1 \geq \sigma < 0$	$0 \geq \sigma < 1$	$1 \geq \sigma < 2$	$2 \geq \sigma < 3$	$3 \geq \sigma$
30 Day	0	0	0	1	0	3	0
21 Day	0	0	0	1	1	3	0
14 Day	0	0	0	3	3	3	0
10 Day	0	0	3	4	1	4	0
7 Day	0	0	2	9	3	4	0
5 Day	0	0	4	11	7	2	0
3 Day	0	2	8	20	8	3	1 (3.3σ)
1 Day	1 (-2.2σ)	13	30	48	30	6	1 (3.8σ)

Table 2. Preliminary distribution of significances found in Mrk 421 source bin for various timescales. Entries are not correlated for individual timescales. Both entries with $> 3\sigma$ correspond to the transit beginning on MJD 2001 (April 2, 2001).

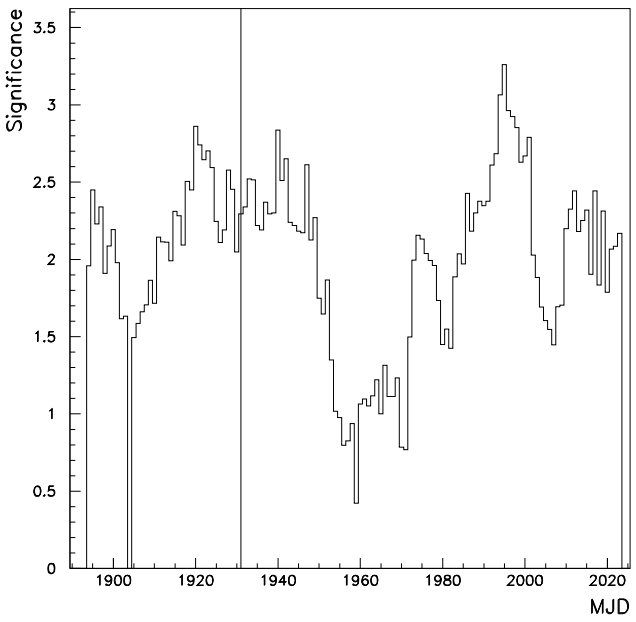

Fig. 2. Preliminary Mrk 421 light curve as seen by Milagro. The vertical line represents the date when the improved calibrations were implemented.

cumulative significance is calculated for each transit combined with the next 29 transits of data. Although points on this plot are correlated, it does give an indication of the light curve observed by Milagro. However, the event rate in Milagro varied during the time period studied and may be partially responsible for some of the fluctuations seen.

Once again accounting for trials becomes important. In order to generate an independent data set, only points every 30 transits, or the relevant timescale, were used. The date that the new calibrations were implemented was chosen as the reference point. This was done to keep flaring information from the 2 data sets separate. Table 2 shows the breakdown of excess significance observed on the 8 timescales during the 129 total transits. This indicates that Milagro observed detectable levels of gamma-ray emission from Mrk 421 on time scales as low as 10 days. The absence of any excess greater than 4 sigma for the 8 timescales, indicates no single burst was solely responsible for the excess detected by Milagro.

9 Conclusions

Milagro has detected Mrk 421 during its bright flare in early 2001. The detection of significant excess in the direction of Mrk421, on timescales as low as 10 days, confirms that Milagro is capable of observing flaring behavior associated with AGN. This coupled with the detector's ability to monitor AGN during daytime transits, when observations with Air Cherekov Telescopes are impossible, show that the Milagro gamma-ray observatory is poised to make significant contributions to the field of TeV astrophysics. Updated results will be presented at this conference for all 26 AGN, from a more lengthy data set, involving the new calibrations as much as possible.

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References

R. Atkins et al., TeV Observations of Markarian 501 with the Milagrito Water Čerenkov Detector, Astrophysical Journal Letters, 525, L25-L28, 1999.

R. Atkins et al., Milagrito, a TeV Air-Shower Array, Nuclear Instruments and Methods in Physics Research Section A, 449, 478-499, 2000.

T. Li & Y. Ma, Analysis Methods for Results in Gamma-Ray Astronomy, Astrophysical Journal, 272, 317-324, 1983.

R. Mukherjee et al., EGRET Observations of High-Energy Gamma-Ray Emission from Blazars: an Update, Astrophysical Journal, 490, 116-135, 1997.

E.S. Perlman, X-ray Selected BL Lacs and Blazars, Proceedings of the GeV–TeV Gamma-Ray Astrophysics Workshop: Towards a Major Atmospheric Čerenkov Telescope VI, Snowbird, Utah, August 13-16, 1999.

C. Sinnis et al., these conference proceedings.

G. Sullivan et al., these conference proceedings.