Monitoring the Northern Sky for Sources of TeV Gamma Rays

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Abstract

At the present time there are fewer then 10 confirmed sources of TeV gamma rays. While this lack of sources is partially due to the sensitivity of current instruments, it may also be due to the small field-of-view of current instruments coupled with the transient nature of astrophysical sources of TeV gamma rays. Milagro is a new type of extensive air shower array that uses water as the detecting medium and has the ability to continuously monitor the entire overhead sky for transient and steady sources of TeV gamma rays. Here the analysis of 2.4 years of data searching for steady TeV gamma-ray emission in the northern hemisphere is presented. Two sources have been detected: the Crab nebula and Mrk 421. A third region at a location of 79.44 ± 1.0 ra and 26.26 ± 0.7 declination is the third brightest region in the northern sky. After accounting for the trials associated with searching the entire northern hemisphere this region is not statistically significant. At the conference results from searches for transient emission on timescales of 1 week and greater will be presented.

1. Introduction

The Milagro gamma-ray observatory has 723 photomultiplier tubes (PMTs) submerged in a 24-million liter water reservoir. The detector is located at the Fenton Hill site of Los Alamos National Laboratory, about 35 miles west of Los Alamos, NM, at an altitude of 2630 m asl (750 g/cm^2). The reservoir measures 80m $\times$ 60m $\times$ 8m (depth) and is covered by a light-tight barrier. Each PMT is secured by a Kevlar string to a grid of sand-filled PVC sitting on the bottom of the reservoir. The PMTs are arranged in two layers, each on a 2.8m x 2.8m grid. The top layer of 450 PMTs (under 1.4 meters of water) is used primarily to reconstruct the direction of the air shower. By measuring the relative arrival time of the air shower across the array the direction of the primary cosmic ray can be reconstructed with an accuracy of roughly 0.75°. The bottom layer of 273 PMTs (under 6 meters of water) is used primarily to discriminate between gamma ray initiated air showers and hadronic air showers.

The discrimination of the cosmic ray background is described in detail in [1]. The background rejection uses a paramter known as compactness which is

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equal to the number of PMTs in the bottom layer with more than 2 PEs divided by the number of PEs in the PMT with the largest pulse height (in the bottom layer). The Monte Carlo triggered cosmic-ray sample consists of 80% protons and 20% helium nuclei. The effect of heavier nuclei is ignored. A requirement that the compactness be greater than 2.5 retains 50% of the gamma rays while removing 90% of the cosmic ray background, resulting in an improvement in sensitivity of 1.6 (i.e. the significance of a signal, expressed as standard deviations, will on average, be 1.6 times greater after the application of the compactness criteria on the data). All data used in this analysis has been required to have compactness greater than 2.5

Milagro began data taking in 1999. The dataset presented here begins on December 15, 2000 and ends on May 1, 2003. The trigger rate during this time varied from 1500 Hz to 1800 Hz. The data is calibrated and reconstructed in real time. Except for selected regions of the sky only the reconstructed information is saved to disk. This analysis utilizes the reconstructed data set. We have searched the nothern hemisphere for steady and transient sources of TeV gamma rays. For the transient searches timescales of 1 week and larger were selected with a factor of two increase in duration between timescales. The results from all timescales will be presented at the conference. Here we will present the results from the D.C. analysis of the entire 2.4 years of data.

2. Analysis Technique

Each day two maps of the sky are constructed: a signal map (comprised of the actual numbers of events coming from each bin in the sky) and a background map (comprised of an estimate of the background from each bin in the sky). The maps are binned in 0.1×0.1 degree bins. To estimate the background a technique called "direct integration" is used. Details of this method may be found in [1]. The method makes use of the fact that the earth rotates and that the detector response is soley a function of local coordinates and time. The underlying assumption of the method is that the shape of the detector response does not vary over the period during which the background is accumulated (here two hours). This method naturally accounts for rate variations in the detector and makes a high statistics measurement of the background (roughly 12 times as much background as signal is accumulated for each point in the sky).

The daily maps are summed to form maps for the longer duration searches. For each search duration start times of the search window are staggered by 1/2 of the search duration. For example in the search for 1 week long transients start times of the search window begin 1 week and 3 days apart.

To search the skymaps for evidence of a source of TeV gamma rays a bin of size 3 degrees in declination (δ) by $3.0/\cos(\delta)$ degrees in right ascension is used. The 0.1×0.1 bins in the maps are summed to form these larger bins. A large bin

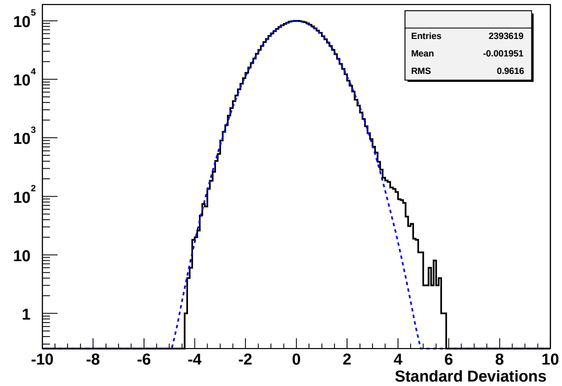

Fig. 1. The distribution of significances of the excesses and deficits in the analysis of the D.C. skymap of the northern hemisphere.

is formed with its center on each 0.1×0.1 degree bin. The data from each signal map and background map are then compared. To calculate the significance of each excess or defecit the prescription of Li and Ma [2] is used, with the caveat that the signal region is not used to estimate the background.

3. Results

Figure 1 shows the distribution of excesses (in standard deviations) for all bins in the map comprised of the entire 2.4 years of data. There is a clear excess number of points in the sky with greater than 4 standard deviation excess. The bullk of this excess can be attributed to two sources of TeV gamma rays: the Crab nebula and the active galaxy Mrk 421.

Figure 2 shows the map of the northern hemisphere in TeV gamma rays over the past 2.4 years. The Crab and Mrk 421 are clearly visible in the map. At the location of the Crab the significance of the excess is 4.4 standard deviations. The largest excess near the Crab is 0.4 degrees from the nominal position of the Crab and has a significance of 5.66 σ. While this is consistent with statistical fluctuations the possibility of a systematic pointing error on the order of 0.4 degrees can not be excluded. At the location Mrk 421 the significance of the excess is 4.4 standard deviations. The third brightest region in the sky is located near the crab at a location of 79.44 ± 1.0 ra and 22.26 ± 0.7 δ. With a significance of 4.5σ this region is consistent with the expected fluctuations in the background given the large number of trials incurred in examining the entire sky.

Both the energy response and the sensitivity to gamma ray sources of Milagro are dependent upon the declination of the source. For example the median energy for a source with an $E^{-2.4}$ spectrum at a declination between 25 and 45 de-

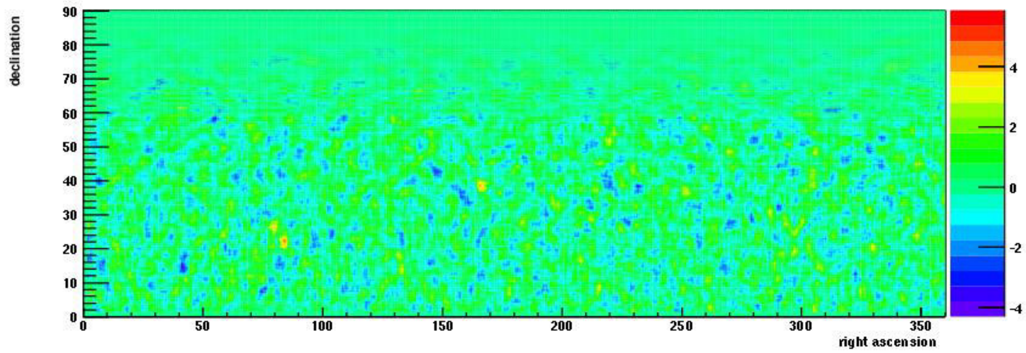

Fig. 2. The northern hemisphere as seen in TeV gamma rays. At each point the excess is summed over a 3 degree by $3/\cos(\delta)$ bin and the significance of the excess in standard deviations is plotted.

grees is ∼3 TeV and rises to ∼10 TeV for a source at a declination below 5 degrees or above 70 degrees. Detailed flux limits will be presented at the conference.

4. Conclusions

A search for continuous TeV gamma ray sources in the northern hemisphere (over the past 2.4 years) has been performed. Two previously known sources have been detected: the Crab nebula and the active galaxy Mrk 421. From this one can conlcude that there are no other sources of TeV gamma rays in the northern hemisphere with a time averaged luminosity much greater than that of the Crab nebula. At the conference we will present the results of the search for transient sources of TeV gamma rays and upper limits on the flux of gamma rays from undiscovered sources in the northern hemisphere.

5. References

1. Atkins, R. et al. 2003, submitted to ApJ.
2. Li, T.P and Ma, Y.Q. 1983, ApJ, **272**, 317