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Milagro observations of potential TeV emitters

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ABSTRACT

This paper reports the results from three targeted searches of Milagro TeV sky maps: two extragalactic point source lists and one pulsar source list. The first extragalactic candidate list consists of 709 candidates selected from the *Fermi-LAT* 2FGL catalog. The second extragalactic candidate list contains 31 candidates selected from the TeVCat source catalog that have been detected by imaging atmospheric Cherenkov telescopes (IACTs). In both extragalactic candidate lists Mkn 421 was the only source detected by Milagro. This paper presents the Milagro TeV flux for Mkn 421 and flux limits for the brighter *Fermi-LAT* extragalactic sources and for all TeVCat candidates. The pulsar list extends a previously published Milagro targeted search for Galactic sources. With the 32 new gamma-ray pulsars identified in 2FGL, the number of pulsars that are studied by both *Fermi-LAT* and Milagro is increased to 52. In this sample, we find that the probability of Milagro detecting a TeV emission coincident with a pulsar increases with the GeV flux observed by the *Fermi-LAT* in the energy range from 0.1 GeV to 100 GeV.

1. Introduction

The Milagro gamma-ray observatory was a water Cherenkov detector located near Los Alamos, New Mexico, USA at latitude 35.9° north, longitude 106.7° west and altitude 2630 m [4]. Milagro recorded data from 2001–2008 and was sensitive to extensive air showers initiated by gamma-rays with energies from a few hundred GeV to ~100 TeV. Unlike atmospheric Cherenkov telescopes, Milagro had a wide field of view and it was able to monitor the sky with a high duty cycle (>90%).

The Milagro collaboration has performed blind source searches and found a number of TeV sources ([9,1] We refer to this as

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Milagro Galactic Plane Surveys). Blind searches for excess events over the full sky have a high probability of picking up random fluctuations. Therefore, after trials correction, a full sky blind search is less sensitive than searches using a smaller predefined list of candidates. The *Fermi Large Area Telescope (Fermi-LAT)* collaboration published such a list known as the Bright Source List or 0FGL list [2]. In a previous publication, Milagro reported a search using 0FGL sources identified as Galactic sources [3], which we will refer to as the Milagro 0FGL paper.

We report here two Milagro targeted searches for extragalactic sources. The first extragalactic candidate list is compiled from the extragalactic sources in the 2FGL catalog [19]. The analysis presented in this paper looks for the TeV counterparts of these sources. The second extragalactic candidate list is made from the TeVCat catalog [20] of extragalactic sources. While TeVCat detections may include transient states of variable extragalactic sources, this search looks for long-term time averages by integrating over the full Milagro data set. However, it is not appropriate to use the second extragalactic candidate list to perform a population study as it has candidates detected from several instruments with different sensitivities.

Our previous Milagro 0FGL publication found that the *Fermi-LAT* bright sources that were measured at or above 3 standard deviations in significance (3σ) by Milagro were dominated by pulsars and/or their associated pulsar wind nebulae (PWN). Therefore, in this paper we extend the previous Galactic search by making a candidate list from the pulsars in the 2FGL source list, and search for TeV emission from the sky locations of gamma-ray pulsars detected by the *Fermi-LAT*. The angular resolution of Milagro ($0.35^\circ < \delta\theta < 1.2^\circ$) is not sufficient to distinguish the PWN from the pulsar.

2. Methodology

2.1. Construction Of candidate lists

The first candidate list, which will be referred to as the 2FGL Extragalactic List, is derived from the 2FGL catalog by looking for sources off the Galactic plane ($|b| > 10^\circ$) that have no association with pulsars. There are 709 *Fermi-LAT* sources within Milagro's sky coverage ($-7^\circ <$DEC$< 80^\circ$), of which 72% are associated with blazars. Among these blazars 4 are firmly identified as BL Lac[7] blazars and 12 are firmly identified as FSRQ.[8] type of blazars.

The second extragalactic candidate list, which we will call the TeVCat Extragalactic List, is taken from TeVCat, an online gamma-ray source catalog (http://tevcat.uchicago.edu). As of February 8th, 2012 it contained 135 sources, of which 31 were located off the Galactic plane and within Milagro's sky coverage. These 31 sources were all detected with Cherenkov telescopes and 23 are identified as BL Lac objects.

There are 52 sources in the 2FGL catalog associated with pulsars which are in the Milagro's sky coverage. Twenty of these pulsars were already considered as candidates in the Milagro 0FGL publication. So the third candidate list, which will be called the Pulsar List, consists of only the 32 new pulsars. Of these, 17 were identified as pulsars by pulsations seen in *Fermi-LAT* data and the remaining 15 sources were labeled as pulsars in 2FGL because of their spatial association with known pulsars.

2.2. Spectral optimizations

In order to optimize the sensitivity to photon sources, Milagro sky maps are constructed by plotting the location for each event with a weight based on the relative probability of it being due to a primary photon or hadron [4]. The weight calculation depends on the assumed photon spectrum and can be suboptimal (but not incorrect) if the weight optimization hypothesis is considerably different from the actual source spectrum. The weights are therefore optimized separately for two hypotheses.

For the extragalactic candidate lists, a power law with spectral index $\alpha = -2.0$ with a 5 TeV exponential cut-off ($E^{-2.0}e^{-\frac{E}{5\,\mathrm{TeV}}}$) was assumed. This choice reflects the fact that when TeV gamma-rays travel cosmological distances they are attenuated due to interactions with photons from the extragalactic background light [12] with the result that the energy spectrum of extragalactic sources cut off at high energies. This spectral assumption is also similar to the power law spectral index and the cut-off energy measured for Mkn 421 and Mkn 501 by the Whipple observatory [16]. However, the choice of 5 TeV cut off might reduce the sensitivity of Milagro to the AGNs with lower cut off energies. For the Pulsar List, a power law with spectral index $\alpha = -2.6$ with no TeV cut-off is used, as was done for the previous Milagro 0FGL and Galactic Plane Survey papers.

2.3. Source detection technique

The expected significance at a sky location with no true emission is a Gaussian random variable with mean 0 and unit standard deviation [9]. A common treatment of N candidate searches is to use a trials correction technique. Here one choose a significance threshold, calculate the tail probability (p-value) λ, and adjusts the p-value threshold to $\frac{\lambda}{N}$. The purpose of the trials correction is to maintain, at the value λ, the probability of a background fluctuation producing one or more false discoveries among the N searches.

The False Discovery Rate (FDR) technique discussed in [18] offers some advantages over the trials correction technique. Instead of controlling the expected probability of having even one false detection, FDR controls the *expected fraction* of false discoveries among a set of detections; that is, it controls the contamination fraction of the *lists* of associations, rather than the probability of a random individual association being accepted.[9] The key input parameter is again a probability λ, but now λ represents the expected fractional contamination of any announced set of detections. Based on this input parameter, the method dynamically adjusts the detection threshold but in a way that depends on the properties of the entire list of search significances (converted into p-values). This dynamic adjustment is sensitive to whether the distribution of p-values is flat (as would be expected if there were no detectable sources) or skewed to small p-values (i.e. large significances). This adjustment lowers the significance threshold for detection if a list is a "target-rich environment" in such a way that the expected fraction of false discoveries among the announced detections remains at the fraction λ. In particular, the most significant candidate is required to have a p-value of λ/N just as in the trials-correction method, but the n-th most significant candidate need only have a p-value less than $\lambda \times n/N$. As a result, this technique has a higher efficiency for finding real detections, while producing the same results as a trials-correction method in target-poor environments where the only decision is whether to report zero or one detections. The method adjusts for both the length of the search list and the distribution of the significances found within the search lists. However, we note that as a result, a given candidate location might pass the FDR criteria on one search list, but fail in another. We also emphasize that λ controls the *expected* contamination, i.e. averaged over potential lists of associations, not the contamination fraction on a specific list.[10] The

[7] BL Lac is a type of active galaxy of known to be strongly γ-ray emitting objects [11].

[8] Flat Spectrum Radio Quasar.

[9] The required calculations are quite simple and can be implemented in a spreadsheet after the significances of the searches on a list are calculated.

[10] For example, in an environment with no real sources, one expects to report an empty list $(1-\lambda)\times 100\%$ of the time, and about $\lambda \times 100\%$ of the time one would report a list having at least a single (false) candidate.