Evidence for a New Source of TeV Gamma Rays from Angular Correlation Studies of the Milagro and Tibet Northern Sky Surveys

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We have examined the directional cross-correlation of statistical "hot-spots" between a Northern Sky TeV Gamma Ray Survey by the Milagro Observatory and a similar survey by the Tibet Array. We find the directions of these hot-spots are angularly uncorrelated between the two surveys for large angular separations ($\Delta\theta > 4°$), but there appears to be a statistically significant correlation between hot-spot directions for $\Delta\theta < 1.5°$. Independent simulations indicate the chance probability for the occurrence of this correlation is approximately 10^{-4}, implying the existence of one or more previously unobserved TeV gamma-ray sources in these directions. The data sets are consistent with both point-like sources or diffuse sources with extent of 1°-2°. The source may be steady or may be time-episodic, and could also possess a non-conventional gamma-ray energy spectrum above 1-2 TeV.

1. Introduction

The field of TeV γ-ray astronomy has recently reached maturity with the advent of the second generation of imaging atmospheric Cherenkov telescopes (IACT). Namely, the HESS observatory, which has been completed, and the VERITAS and MAGIC observatories, which are near completion. However, still lacking from the field is a wide field of view instrument that has comparable sensitivity to the IACTs.

IACT instruments are well suited for the observation of point sources that have a steady γ-ray flux. However, due to there small field of view and low duty cycle, they are not well suited for observing transient sources (GRBs) and extended sources (the Galactic Plane and Giant Molecular Clouds). Observations of extended sources can easily be done by large field of view instruments, but these instruments don't have the sensitivity of the IACTs. As such, one may infer the existence of sources by searching for evidence of angular correlation in the all sky surveys performed by these wide field of view detectors. If sources exist at flux levels below the detection threshold, than there may appear correlations in the location of statistical "hot-spots". We have carried out such an analysis using published data from the Milagro observatory and the Tibet Air Shower array.

The Milagro observatory and the Tibet Air Shower array are wide field of view TeV γ-ray (1 TeV = 10^{12} eV) observatories that are capable of monitoring the northern hemisphere sky on both long and short timescales. The Tibet and Milagro detectors have similar exposures and angular resolutions ($\leq 1°$) as verified by moon shadow analysis [7, 23]. Based on the moon shadow analysis Tibet reports a systematic pointing error of 0.1° while Milagro reports an overall angular resolution of 0.75° including pointing errors. Recent Tibet [6, 13] and Milagro [9] northern-hemisphere sky surveys have detected statistical 'hot-spots' where excessive numbers of cosmic-rays ($> 4\sigma$ above expected background level) appear to be concentrated from specific directions. Two of these hot-spots are identified with well known TeV sources [5, 8, 10]. In each sky survey, the remaining hot-spots are consistent with random statistical fluctuations in the cosmic ray background rate in each direction. However, if real TeV γ-ray sources exist with fluxes just below the sensitivity of these observatories, then one may expect to see angular correlation between the directions of the Milagro sky-survey hot-spots and the Tibet sky survey hot-spots, with an angular correlation distance equal to a convolution of the angular resolution functions of the two detectors. This may be complicated by pointing errors for weak point sources and detector systematics. Furthermore, it is unclear what angular correlation to expect for a diffuse TeV γ-ray emission region.

2. The All Sky Surveys

Milagro and Tibet have both conducted all sky surveys of the northern sky by plotting the arrival direction of γ-rays and cosmic rays in right ascension (RA) and declination (δ). With this data a binned all sky map is formed and the number of events in each bin is counted. Once the bin content is known the background can be estimated and the statistical significance of the bin can be found.

In the the Tibet survey that background was determined by the equi-declination method [6]. This method assumes that the background in the same δ band as the source, constitutes a smooth background in RA. Therefore, the background (N_{off}) in the on source bin can be estimated by a smooth fit to the off source bins in the same δ band. The Tibet analysis, this fit was done by χ^2 minimization to a second order polynomial.

The Milagro analysis uses a more robust method known as direct integration to estimate the background [4, 10, 19]. The two assumption of direct integration are that cosmic rays form an isotropic background, and that the acceptance of the detector is independent of trigger rate over some time period (in Milagro the time period used was two hours). The expected background in the bin (N_{exp}) is then given by

$$N_{exp}[RA, \delta] = \int\int E(HA, \delta)R(t)\epsilon(HA, RA, t)dtd\Omega. \tag{1}$$

The *E(HA,δ)* term is the acceptance of the detector in local coordinates (HA and δ), *R(t)* is the trigger rate over some time window (in the case of [9] the window is two hours), and $\epsilon(HA, RA, t)$ is a mapping function between local coordinates and celestial coordinates as a function of time.

Once the expected background is known and the number of observed events is known, the significance of the observation can be computed. The Milagro survey used the method of Li and Ma [17], while the Tibet survey reported its significance according to

$$S_\sigma = \frac{N_{on} - N_{off}/m}{\sqrt{N_{off}}/m}. \tag{2}$$

Where N_{on}, and N_{off} are the observed number of signal events and the estimated number of background events, and m is the ratio of exposures to the off source bins to the on source bins. Due to statistical fluctuations in the observed number of events one would expect a normal distribution of significance over the whole sky. Any positive significance cannot be claimed as an observation unless it is in excess of the expected distribution. Excluding known sources from the distribution no statistically significant excess were found in the surveys.

The Tibet 2001 sky survey analysis [6] found 18 hot-spots (above 4σ) which are un-associated with any known TeV γ-ray source. The Tibet 2003 sky survey [13] found 21 hot spots which are un-associated with known TeV γ-ray sources, but only report the directions of three of these hot-spots in their paper. In each Tibet survey a different non-overlapping data set was used. Thus the two Tibet surveys should be independent of each other. The Milagro analysis [9] reports the directions of 9 unidentified hot-spots. Off these hot spots, we found three pairs with close proximity to each other. Listed in table 1 are the locations of these pairs denoted as A,B,and C.

3. Angular Correlation between Milagro Hot Spots and Tibet Hot Spots

As the Tibet 2003 survey only reported a partial list of hot spots, we were unable to do a full comparison with the 2003 survey. To investigate the correlation between the two surveys (the Milagro and the Tibet 2001) we populated a histogram with the angular separation of each pair of hot spots in the two surveys. This is the measured angular correlation. To determine the expected angular correlation between the two surveys, under the assumption that all of the hot spots were due to statistical fluctuations, we populated the region of the sky in each survey, with background events drawn from a uniform distribution in RA and a cos($\delta - latitude$) distribution in δ. Here *latitude* is the specific latitude for each observatory, and δ reflects the range of declination field of view of each observatory. In general the distribution of excesses in the sky should be independent of the region of the sky (assuming the significance is calculated correctly). Once the sky was populated the data was binned in a manner consistent with the technique used by each survey.

Table I Co-located hot-spots from Milagro[9], Tibet 2001[6] and Tibet 2003[13]. The last column shows the upper limits determined by the Milagro group in Crab units. The Tibet 2001 and the Tibet 2003 analyses did not report upper limits.

Pair	**Survey**	**RA**	δ	σ	**Flux Limits**
A	Mil.	306.6	38.9	4.2	0.78
B	Mil.	313.0	32.2	4.5	0.85
C	Mil.	356.4	29.5	4.1	0.84
A	Tib. 03	304.15	36.45	4.0	NA
A	Tib. 01	305.4	37.9	4.15	NA
B	Tib. 01	313.5	32.4	4.27	NA
C	Tib. 01	358.0	30.1	4.10	NA

To estimate the background in each bin the average number of events was used, as determined by averaging over 20 bins in the same δ band. The significance of each bin was then calculated according the the methods described in section 2. Once this was completed, a list of bins with an excess greater than 4σ was made for both the Tibet sky and the Milagro sky. We then computed the angular separation between each hot spot in the Milagro sky and each hot spot in the Tibet sky. This process was repeated 100,000 times. Figure 1 shows the average number of hot spot pairs as a function of angular separation between them as well as the observed correlation.

For large angular separations ($\Delta\theta > 4°$) the measured and simulated correlation distributions are in reasonable agreement. At small angular separations ($\Delta\theta < 2°$), there is a statistically significant deviation from the expected angular correlation distribution for uncorrelated pairs. Three correlated pairs are found, whereas approximately 0.1 are expected. Each of these pairs is found to have angular separation $\leq 1.5°$ between the correlated hot-spots, consistent

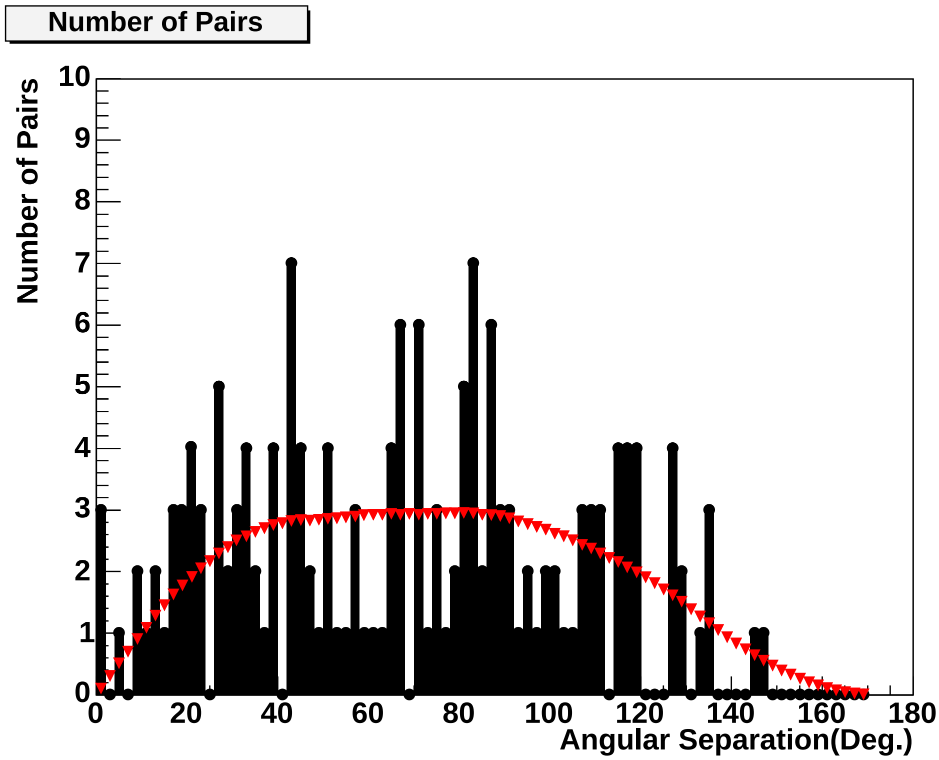

Figure 1: The number of correlated pairs observed in the Tibet 2001 and Milagro surveys (black bars). The expected number of correlated pairs as determined by simulation is shown in red.

with expectations from the combined angular resolution between the two detectors. Figure 2 shows the integral Poisson probability for finding the observed number of correlations, given the mean value from the simulation.

The probability for finding 3 hot-spot pairs (within $1.5°$) between the two surveys can be estimated by placing the 18 Tibet 2001 locations and the 9 Milagro locations randomly and uniformly across the sky in the δ region used in each sky survey. These simulated distributions are then searched for coincident hot-spots and the probability of having N hot-spot correlations with $\Delta\theta < 1.5°$ is compiled from the fraction of simulations which yield N correlated hot-spot pairs. (Method 1). This is a reasonable approximation because the distribution of hot-spots is found to be relatively uniform across the observatory's field of view in both measured sky survey distributions as well as the above uncorrelated pair angular correlation distribution simulations.

The more extensive angular correlation distribution simulations can also be used to independently calculate the probability of observing N hot-spot correlations with $\Delta\theta < 1.5°$ from the fraction of simulations which yield N correlated hot-spot pairs. (Method 2). The results of our these calculations for both methods are presented in Table 2. The calculations of both methods are consistent with each other and indicate

Table II Chance probability of obtaining N pairs of hot spots with an angular separation less the $1.5°$.

N	Method 1	Method 2
0	94.5%	96.1%
1	5.4%	3.7%
2	0.1%	0.16%
3	0.003%	0.011%

that the chance probability of finding 3 uncorrelated hot-spot pairs (within $1.5°$) between the two surveys is small. The Monte Carlo method employed in our analysis takes into account all statistical trials factors except for that associated with the correlation distance $1.5°$. We did not examine correlations on different length scales, but it is important to note from figure 1 that this result is relatively independent of any reasonable choice of the correlation distance between $1.5°$ and $4°$. This would indicate a trials factor for the angular correlation distance of order of magnitude 1.

4. Results and Discussion

Of the three regions of correlation pair A is perhaps the most interesting of the three. More discussion

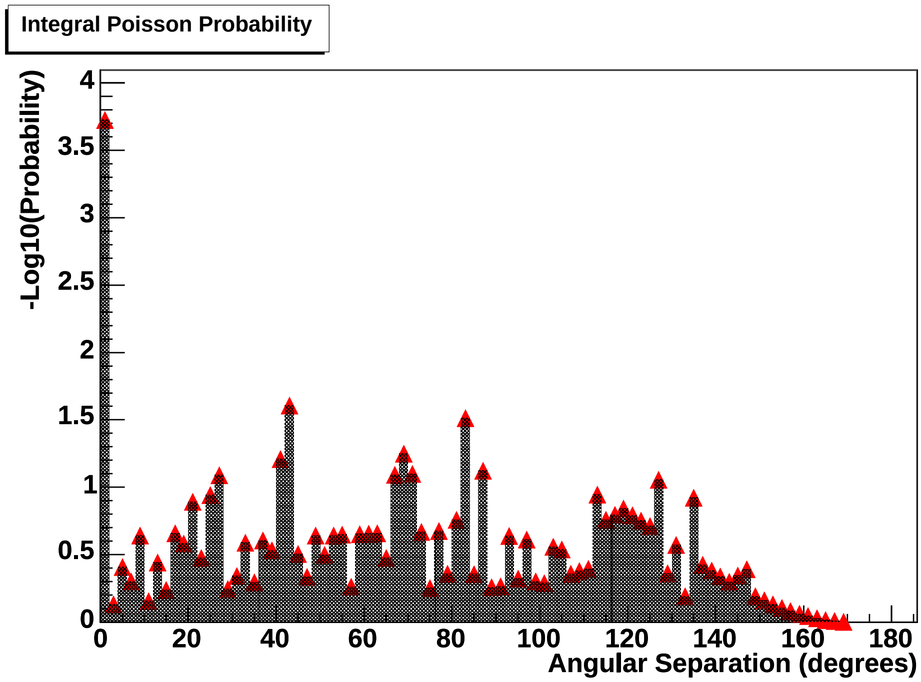

Figure 2: Integral Poisson probability for obtaining the observed number of pairs given the mean expected number of pairs (as determined by simulation) as a function of angular separation. The small probability of observing three pairs at an angular separation of 1.5°. is an indication that unknown sources may exist in surveys

on the other pairs can be found elsewhere [26]. This pair is in a very dense region of the Cygnus Arm and has relatively close proximity to Cygnus OB2 and the unidentified γ-ray source TeV2032 [1] (RA = 308.05, $\delta = 41.52$). Although it is certainly possible that no γ-ray source exists at this location, more recent results from the Milagro observatory seem to indicate the presence of a DC γ-ray source of diffuse origin [24, 25].

4.1. Diffuse γ-ray Emission

It has long been proposed that diffuse γ-rays should be produced by interactions between galactic cosmic rays, the galactic plane, and giant molecular clouds(GMC) [15, 21]. This process is driven by the production and decay of neutral pions.

$$p + p \rightarrow p + p + pions \tag{3}$$
$$\pi^0 \rightarrow \gamma + \gamma \tag{4}$$

Although other channels can contribute, the pion production is the main source of γ-rays from hadronic interactions. In addition to this there could also exist contributions from cosmic ray electrons [12, 22] by the usual methods [11].

Observations by OSO 3[16], SAS 2[14], and COS B[18] show correlation between the spacial structure of the galactic plane and γ-ray emission. More recent observations by EGRET seem have been compared with model predictions and seem to agree surprisingly well between 100 MeV and 1 GeV. At higher energies above 1 GeV there is almost 40% excess in the γ-ray flux (it should be noted that this ≃40% seems to be a moving target). Above 1 GeV the expected contribution to the total flux by neutral pions is roughly 90% and 10% for electrons [20].

In the case of diffuse emission from GMC there are two main sources of the emission (assuming it is hadronic in origin). First the population of cosmic rays could be identical to the average cosmic ray population that we observe locally. In this case the spectrum of the γ-ray emission, once above threshold, should follow the soft cosmic ray spectrum. This is a two-fold problem. First the γ-ray emission scales linearly with local intensity of galactic cosmic rays. Thus the emission would be relatively small due to the low flux of cosmic rays. Calculations by Aharonian[2] place the flux from galactic cosmic rays at

$$J(\geq) \simeq 1.5 \times 10^{-13} \left(\frac{E}{1\ TeV}\right)^{-1.75} \left(\frac{M_5}{d_{kpc}^2}\right) \left[\frac{ph}{cm^2 \cdot s}\right] \tag{5}$$

For energies greater than 1 GeV. Where M_5 is the mass of the cloud in units of the mass of the cloud divided by 10^5 solar masses and d_{kpc}^2 is the distance to the cloud in kiloparsecs. In equation 5 the angular extent of the object is considered to point like. This is obviously not necessarily the case. For larger angular extents observations from pointed instruments can be

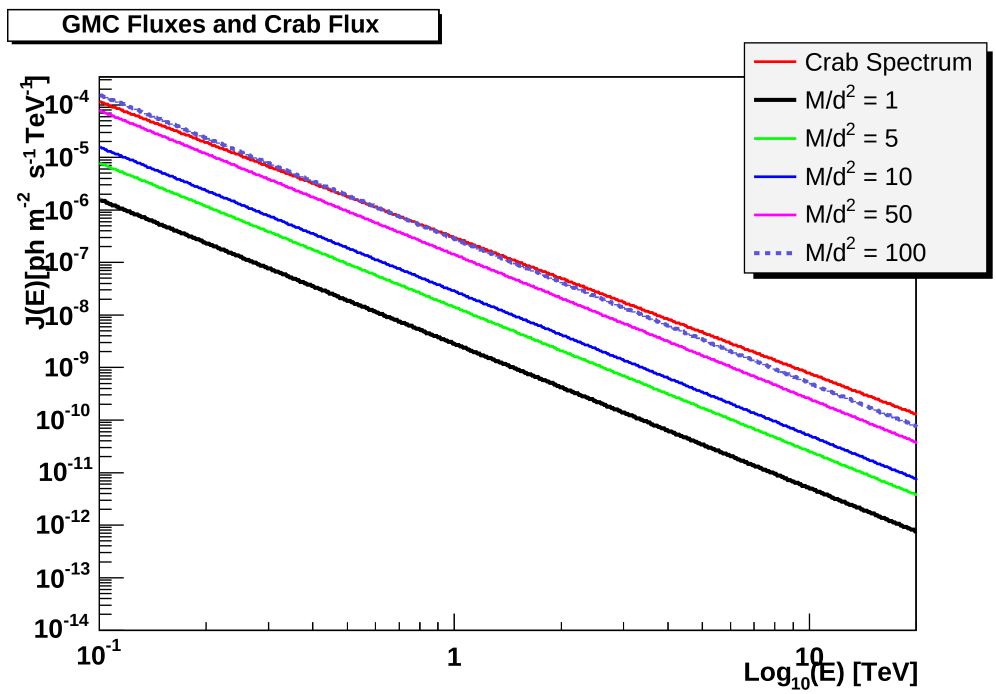

Figure 3: Predicted γ-ray fluxes from GMC for different values of M_5/d^2_{kpc}, assuming the emission is a result of galactic cosmic rays interacting with the GMC. If the source of cosmic rays is local to the GMC, one may expect a harder spectrum. The crab flux is also show for comparison.

complicated.

Figure 3 shows the flux from equation 5 for different values of M_5/d^2_{kpc} for small values on the order of one observations will be difficult due to the low flux. At larger values $M_5/d^2_{kpc} > 10$ the flux approaches 10% of the crab flux at 1 TeV. These fluxes assume a continuation of the spectrum to TeV energies. In addition to this the flux quoted in equation 5 does not include the additional 10% contribution of cosmic-ray electron interactions.

While the number of GMC in the galaxy with values of $M_5/d^2_{kpc} > 10$ are not numerous, observations with second generation instruments may still be fruitful.

Another scenario, and potentially much more promising, is that GMC may exist in the vicinity of cosmic-ray accelerators. Thus, the flux of cosmic rays impacting the GMC may be much higher than the average flux and thus the γ-ray flux may be much higher even for less massive clouds[3]. This scenario has the possibility of revealing the sources of galactic cosmic rays. Additionally the flux from such GMC would follow the harder 2.1 spectrum of the input cosmic ray spectrum. This increases the likelihood of detection.

4.2. Conclusions

The correlation between hot spots in the two surveys imply the existence of at least one new source of TeV γ-rays. In addition, based on recent observations my the Milagro group, these sources may be diffuse in nature and thus difficult to observe with conventional IACT. Based on the published upper limits for the Milagro hot-spots the expected flux from these possible observations must be ~ 0.8 times the flux from the Crab Nebula in the TeV range in order to have caused these fluctuations, and simultaneously avoided strong direct-detections by the two northern-sky surveys.

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