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Discovery of Localized TeV Gamma-Ray Sources in the Galactic Plane with Milagro

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Abstract: Recent development in the analysis techniques used by the Milagro collaboration significantly improved the sensitivity of the Milagro detector [1, 2]. Using this new technique, a survey of Galactic gamma-ray sources at a median energy of $\sim$ 20 TeV has been performed. This survey covered the region of Galactic longitude $l \in [30^\circ, 220^\circ]$ and Galactic latitude $b \in [-10^\circ, 10^\circ]$ in which eight candidate sources of TeV gamma-ray emission were detected with pre-trials significance $> 4.5\sigma$. Four of these sources were observed with significances $> 4.5\sigma$ after accounting for trials in this region. These four sources include the Crab Nebula and the recently discovered Milagro source MGRO J2019+37 [3]. One of the lower significance sources is coincident with Geminga which is the brightest EGRET source in the Northern Hemisphere sky. Several of these sources appear to be spatially extended with fluxes at 20 TeV ranging from $\sim$ 25% of the Crab flux to nearly as bright as the Crab. In this paper, we will discuss the TeV flux, spatial morphology, and potential counterparts of the new sources.

Introduction

Milagro is a water Cherenkov detector that continuously views the entire overhead sky. The large field-of-view of $\sim$ 2 steradians combined with the long observation time makes Milagro the most sensitive instrument available for the study of large, low surface brightness sources such as the gamma radiation arising from interactions of cosmic radiation with interstellar matter. Recent development in the analysis techniques used by the Milagro collaboration significantly improved the sensitivity of the Milagro detector [1, 2]. In this work, we report on observations of gamma-ray sources in the region of Galactic longitude $l \in [30^\circ, 220^\circ]$ and Galactic latitude $b \in [-10^\circ, 10^\circ]$. In comparison, the HESS atmospheric Cherenkov telescope (ACT) performed a survey of the region $l \in [-30^\circ, 30^\circ]$ and $b \in [-2^\circ, 2^\circ]$ [4]. The median energy of the Milagro survey is $\sim$ 20 TeV compared to $>$ 200 GeV for the HESS survey [4]. At even lower energies, EGRET detected 28 sources above 1 GeV within 10 degrees of the Galactic plane [5]. Fourteen of these sources are in the region surveyed by Milagro. Four of the eight sources observed by Milagro in this survey are detected with post-trials significance greater than 4.5σ. The rest of the sources are detected at lower significances. Six of these TeV sources are coincident with the locations of EGRET sources.

Data Sample and Analysis

The analysis was performed on $\sim$ 6.5 years of data, starting on July 20th, 2000 and ending on January 1st, 2007. In total, 2358 days of on-time data were included. Sources are only observable as they transit through Milagro's field of view (FOV), so a day of data represents approximately 4-6 hours of exposure for any given northern hemisphere source. The new analysis method described in [3] was used to analyze the Milagro data. In this analysis, events are weighted based on the gamma/hadron separation variable A_4. The angular resolution of Milagro improves when this variable is used and further improves for events with higher values of this variable. As a result, events in the signal and background maps are smoothed with the corresponding point spread function (PSF). The statistical significance of the excess or deficit at each point is computed using equation 17 in Li and Ma [6]. The

Dec. (deg)	Flux Sens.	Median Energy	Range(TeV) 10%-90%
0	6.5	40	9-150
10	4.4	27	6-110
20	3.6	22	5-82
30	3.2	19	4-77
40	3.1	19	4-77
50	3.2	23	5-82
60	3.5	26	6-100
70	4.5	38	8-140

Table 1: Sensitivity and energy response for a $\frac{dN}{dE} \propto E^{-2.3}$ spectrum. The flux sensitivity is for a point source in units of 10^{-15}TeV^{-1} s^{-1} cm^{-2} and is quoted at 20 TeV for a 5σ detection. The last column shows the energy range in which the indicated percentages of weighted events fall.

energy threshold and sensitivity of the Milagro detector vary with the zenith angle. Table 1 shows the median energies and relative sensitivities of the Milagro detector as a function of declination for a source with a differential photon power law spectrum with a spectral index $\alpha = -2.3$[1]. The last column shows the energy range in which the indicated percentages of weighted events fall. Flux from a source is computed assuming a differential photon power law spectrum with a spectral index $\alpha = -2.3$ with no cutoff in the spectrum. All fluxes are quoted at 20 TeV, which is approximately the median energy of the gamma rays detected by Milagro. The median energy of the instrument also varies with the spectral shape of the source. However, the uncertainty of the flux at 20 TeV varies only by $< 20\%$ when the spectral index α varies from -2.0 to -2.6.

Results

Figure 1 shows a PSF-smoothed map of the Galactic plane visible to Milargo. The color scale indicates the pre-trials statistical significance of the Milagro excess or deficit at each point. Table 2 gives the location, in Galactic Coordinates, statistical significances, fluxes, angular extent, and counterparts for the eight source candidates identified with a pre-trials significance in the PSF-smoothed map of $> 4.5\sigma$. The two most significant sources among these eight source candidates are the Crab and the published Milagro source MGRO J2019+37 [3]. Two other sources are observed at signifcances greater than 4.5σ post-trials. Those are MGRO J1908+06 and MGRO J2031+41. Therefore the four most significant sources in Table 2 are considered definitive TeV gamma-ray source detections. The rest of the eight source candidates, labeled C1-C4, have post-trials significances less than 4.5σ and are thus regarded as lower confidence detections.

1. **Crab Nebula**, a standard candle for TeV gamma-ray astronomy, is detected at 15.0σ. The flux derived from the Milagro data agrees, within errors, with the flux measured by ACTs [8]. The best-fit location is 0.11° from the pulsar location, which is consistent with the statistical error.

2. **MGRO J2019+37** is the most significant source detected by Milagro after the Crab, 10.4σ pre-trials. This source is one of five Milagro sources or source candidates in the Cygnus region and was discussed in details in [3].

3. **MGRO J1908+06** is the brightest source detected by Milagro after the Crab nebula with a flux that is $\sim$ 80% of the Crab flux. This source was detected with a pre-trials significance of 8.3σ. The location of this source is the closest to the Galactic Center where the diffuse emission is expected to increase. This source is coincident with the GeV source GEV 1907+0557 and with the bright radio, shell type, SNR G40.5-0.5 [9].

4. **MGRO J2031+41** is another source observed in the Cygnus region. This source is observed with a pre-trials significance of 6.6σ and is located in the area with the largest concentration of molecular and atomic gas in this region. Its location is coincident with the EGRET source GEV J2035+4214 and with 3EG J2033+4118 and with the HEGRA source TEV J2032+413.

1. An event-by-event energy estimator is being developed in Milagro that will allow for the determination of the spectral shape of a gamma-ray source seen in Milagro[7].

The flux measured by Milagro is three times as high as that of TEV J2032+413 when extrapolated to 20 TeV. The spatial extent of the Milagro detection of $3.0° \pm 0.9°$ is much larger than the few arcminute extent of the TEV J2032+413 and therefore there must be another source or sources contributing to the Milagro excess.

5. **C1 & C2** both of these sources are in the Cygnus region and have no obvious EGRET, PWN, or SNR counterparts. Among the eight sources, **C1** is the farthest from the Galactic plane at $b = -3.9°$. **C2** might be an extension of **MGRO J2019+37** but is $2.2°$ away.

6. **C3** is positionally coincident with Geminga, the brightest EGRET source in the northern hemisphere sky. The 5.1σ source detected by Milagro is consistent with the Geminga pulsar location. The extent of the source seen in Milagro is $2.8° \pm 0.8°$. The significance of the Milagro excess at the location of the pulsar is 4.9σ in the PSF-smoothed map.

7. **C4** seen at 5.0σ is the source with the smallest significance among the eight sources in the PSF-smoothed map. As can be seen in Figure 1, this source appears to be very elongated. If a $3° \times 3°$ bin is used, the significance increases to 6.3σ.

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Object	Location (l, b)	Error Radius (deg)	Significance pre-trials	Significance post-trials	Flux at 20 TeV $\times 10^{-15}$ $\mathrm{TeV^{-1}\ s^{-1}\ cm^{-2}}$	Extent Diameter (deg)	Counterparts
Crab	184.5,-5.7	0.11	15.0	14.3	10.9 ± 1.2	-	Crab
MGRO J2019+37	75.0, 0.2	0.19	10.4	9.3	8.7 ± 1.4	$1.1° \pm 0.5°$	GEV J2020+3658, PWN G75.2+0.1
MGRO J1908+06	40.4, -1.0	0.24	8.3	7.0	8.8 ± 2.4	$< 2.6°$ (90% CL)	GEV J1907+0557, SNR G40.5-0.5
MGRO J2031+41	80.3, 1.1	0.47	6.6	4.9	9.8 ± 2.9	$3.0° \pm 0.9°$	GEV J2035+4214, TEV J2032+413
C1	77.5, -3.9	0.24	5.8	3.8	3.1 ± 0.6	$< 2.0°$ (90% CL)	- SNR G40.5-0.5
C2	76.1, -1.7	-	5.1	2.8	3.4 ± 0.8	-	-
C3	195.7, 4.1	0.4	5.1	2.8	6.9 ± 1.6	$2.8° \pm 0.8°$	Geminga
C4	105.8, 2.0	0.52	5.0	2.6	4.0 ± 1.3	$3.4° \pm 1.8°$	GEV J2227+6106 SNR G106.6+2.9

Table 2: Galactic Sources and Source Candidates.

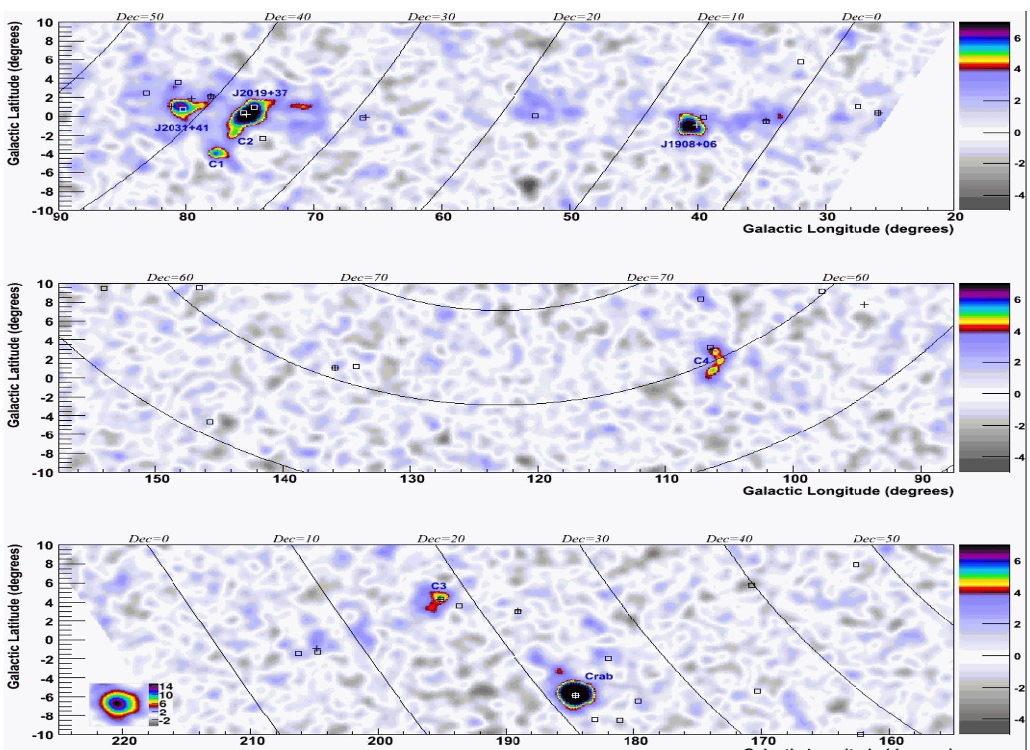

Figure 1: A TeV gamma-ray image of the Galactic plane visible to Milagro. The color code shows the pre-trials significance in this PSF-smoothed map. The color code saturates at 7σ although three of the gamma-ray sources are detected at much higher significances.