TeV GAMMA-RAY SOURCES FROM A SURVEY OF THE GALACTIC PLANE WITH MILAGRO

A. A. ABDO,[1] B. ALLEN,[2] D. BERLEY,[3] S. CASANOVA,[4] C. CHEN,[2] D. G. COYNE,[5] B. L. DINGUS,[4] R. W. ELLSWORTH,[6]
L. FLEYSHER,[7] R. FLEYSHER,[7] M. M. GONZALEZ,[8] J. A. GOODMAN,[3] E. HAYS,[3] C. M. HOFFMAN,[4] B. HOPPER,[3]
P. H. HÜNTEMEYER,[4] B. E. KOLTERMAN,[7] C. P. LANSDELL,[3] J. T. LINNEMANN,[1] J. E. MCENERY,[9] A. I. MINCER,[7] P. NEMETHY,[7]
D. NOYES,[3] J. M. RYAN,[10] P. M. SAZ PARKINSON,[5] A. SHOUP,[11] G. SINNIS,[4] A. J. SMITH,[3] G. W. SULLIVAN,[3] V. VASILEIOU,[3]
G. P. WALKER,[4] D. A. WILLIAMS,[5] X. W. XU,[4] AND G. B. YODH[2]

ABSTRACT

A survey of Galactic gamma-ray sources at a median energy of ∼20 TeV has been performed using the Milagro Gamma-Ray Observatory. Eight candidate sources of TeV emission are detected with pretrial significances >4.5 σ in the region of Galactic longitude $l \in [30°, 220°]$ and latitude $b \in [-10°, 10°]$. Four of these sources, including the Crab Nebula and the recently published MGRO J2019+37, are observed with significances >4 σ after accounting for the trials. All four of these sources are also coincident with EGRET sources. Two of the lower significance sources are coincident with EGRET sources, and one of these sources is Geminga. The other two candidates are in the Cygnus region of the Galaxy. Several of the sources appear to be spatially extended. The fluxes of the sources at 20 TeV range from ∼25% of the Crab flux to nearly as bright as the Crab.

Subject heading: gamma rays: observations

1. INTRODUCTION

A survey of the entire northern hemisphere sky for sources of TeV gamma rays has been performed using the Milagro Gamma-Ray Observatory (Atkins et al. 2004). This Letter reports on observations of sources in the region of Galactic longitude $l \in [30°, 220°]$ and latitude $b \in [-10°, 10°]$. This survey is at a higher energy of ∼20 TeV and in a different region than the survey performed by the HESS atmospheric Cerenkov telescope (ACT) above 200 GeV. The HESS survey covered $l \in [-30°, 30°]$ and $b \in [-2°, 2°]$ and resulted in the detection of 14 new sources (Aharonian et al. 2006b). At even lower energies, EGRET on the *Compton Gamma Ray Observatory* detected 80 sources above 100 MeV (Hartman et al. 1999) and 28 sources above 1 GeV (Lamb & Macomb 1997) within 10° of the Galactic plane. Fourteen of these GeV sources are in the region surveyed by Milagro. Most of the EGRET sources and several of the TeV sources are unidentified without counterparts at lower energies. However, the improved localizations of HESS have led to identification of supernova remnants (SNRs; Aharonian et al. 2004a), pulsar wind nebulae (PWNe; Aharonian et al. 2005c), and molecular clouds (Aharonian et al. 2006a) as emitters of TeV gamma rays.

In the Milagro data, four sources (including the Crab) are detected with posttrial significances greater than 4 σ, and four additional lower significance candidates are identified. Six of these eight TeV excesses are coincident with the locations of EGRET sources. Many of these sources have stringent upper limits at TeV energies, such as those from the Whipple Ob-

servatory (Fegan et al. 2005). However, these upper limits weaken for extended sources by the ratio of the radius of the source to the angular resolution. The angular resolution of Milagro is approximately an order of magnitude larger than ACTs but is less than half that of EGRET, resulting in little reduction in sensitivity for sources up to ∼2° diameter. The TeV flux, spatial morphology, and potential counterparts of these new sources are discussed below.

2. ANALYSIS

The analysis was performed on 2358 days of data collected by Milagro during the operational period from 2000 July 19 through 2007 January 1. Data from the last 3 years of operation were collected after the completion of the outrigger array, which substantially increased the sensitivity of Milagro, particularly at high energies. The Milagro data were analyzed using the method described in Abdo et al. (2007), in which the events are weighted based on the gamma/hadron separation parameter (A_4). The signal and background maps are smoothed with the point-spread function (PSF), which varies based on the number of hits in the events. The statistical significance of the excess or deficit is computed using equation (17) in Li & Ma (1983).

Milagro's latitude is 36° north, where the Galactic center and central bulge are outside the field of view. In this survey, only events with zenith angle less than 45° are included, which covers declinations north of $\delta = -7°$. The energy threshold and sensitivity of Milagro vary with zenith angle. As seen in Table 1, the best sensitivity is achieved for sources that transit through zenith. The sensitivity is degraded by less that a factor of 2, even for sources that transit at 30° from zenith. Table 1 also gives the median energy and relative sensitivity of the instrument as a function of declination for an assumed differential photon power-law spectrum of spectral index $\alpha = -2.3$.

The background at a given location in celestial coordinates is found using the method described in Atkins et al. (2003), with the modification that the events are weighted. The signal map is searched for excesses over the background map with a statistical significance >4.5 σ. The event excess around each source candidate is fit to a two-dimensional Gaussian to determine the

[1] Michigan State University, East Lansing, MI.
[2] University of California, Irvine, CA.
[3] University of Maryland, College Park, MD.
[4] Los Alamos National Laboratory, Los Alamos, NM.
[5] University of California, Santa Cruz, CA.
[6] George Mason University, Fairfax, VA.
[7] New York University, New York, NY.
[8] Instituto de Astronomia, Universidad Nacional Autonoma de Mexico, DF, Mexico.
[9] NASA Goddard Space Flight Center, Greenbelt, MD.
[10] University of New Hampshire, Durham, NH.
[11] Ohio State University, Lima, OH.

DECL. (deg)	FLUX SENSITIVITY[a]	ENERGY RANGE (TeV)	
		Median	10%–90%[b]
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

[a] Differential flux sensitivity at 20 TeV in units of 10^{-15} TeV^{-1} s^{-1} cm^{-2} for a 5 σ detection of a point source.
[b] Energy interval containing the central 80% of weighted events that are used in the analysis.

location, spatial extent, and flux. The average angular resolution[12] of these weighted events is 1.1° and has been measured with observations of the Crab. Astrophysical sources are better described by a top-hat function than a Gaussian; however, a Gaussian approximates a top hat of less than a few degrees diameter that is convolved with the Milagro PSF. Therefore, the Gaussian σ is used to constrain the diameter of the top-hat function that best fits the angular extent of the source.

The excess above the measured background is calculated from the volume of the fit two-dimensional Gaussian. This calculation results in a larger uncertainty than implied by the significance of the detection, but it properly accounts for the flux of extended sources. The excess is converted to a flux using CORSIKA (Heck et al. 1998) to simulate the air showers and GEANT4 (Agostinelli et al. 2003) to simulate the detector. The source fluxes are computed assuming a differential photon spectrum of a power law with spectral index $\alpha = -2.3$ with no cutoff. This is the average spectrum for Galactic sources observed by HESS (Aharonian et al. 2006b). The flux is quoted at 20 TeV, which is approximately the median energy of the gamma rays from the sources detected by Milagro, as seen in Table 1. The median energy of Milagro varies with source spectra and declination; however, the uncertainty in the flux at 20 TeV is relatively insensitive to the assumed spectrum and varies by only <20% when α varies from -2.0 to -2.6.

3. RESULTS

Figure 1 shows a PSF-smoothed map of the Galactic plane, with the color scale indicating the statistical significance of the Milagro excess or deficit at each point. Table 2 gives the locations, fluxes, statistical significances, angular extents, and counterparts for the eight source candidates identified with a pretrial significance in the PSF-smoothed map of >4.5 σ. Because several of the candidates are extended beyond the PSF of Milagro, the maximum pretrial significance for a search with a larger bin of size 3° × 3° is also given in Table 2. However, the posttrial significances are not based on this a posteriori observation but are calculated from the PSF-smoothed pretrial significances. A Monte Carlo simulation is used to account for the trials involved in searching this 3800 deg^2 region. This simulation predicts that 4% of such searches would result in at least one source with >4.5 σ pretrial significance anywhere in the region due to back-

[12] To be consistent with HESS and EGRET, the angular resolution is described by the radius that contains 68% of the signal events from a point source. In previous publications, the σ of the Gaussian function was referenced, which is ~0.7°.

ground fluctuation. The list of eight candidates includes the Crab and MRGO 2019+37, which was previously reported (Abdo et al. 2007). Excluding these previously known gamma-ray sources, six new candidates are identified. The two most significant of these, MGRO J1908+06 and MGRO J2031+41, exceed 4.5 σ after accounting for trials. Therefore, the four most significant sources in Table 1 are considered definitive TeV gamma-ray source detections. The remaining four source candidates, labeled as C1–C4, have posttrial significances of less than 4.5 σ and are regarded as lower confidence detections.

Diffuse Galactic TeV emission is also expected from interactions of the cosmic-ray electrons and hadrons with interstellar gas and radiation that is located far from the accelerators that produce the cosmic rays. This nonisotropic diffuse gamma-ray background will contribute to the observed flux of a source. Diffuse emission is particularly bright in the Cygnus region, where five of the eight candidate sources are located. The GALPROP model (Strong et al. 2004) predicts that the TeV gamma-ray diffuse emission flux is 3–7 times lower than the observed flux in the large Cygnus region defined as $l \in [65°, 85°]$ and $b \in [-2°, 2°]$ (Abdo et al. 2007). For individual sources near high concentrations of matter, the diffuse emission will be a larger fraction of the quoted flux. However, due to uncertainties in the model predictions, the diffuse emission was not subtracted from the source fluxes.

The Crab Nebula, a standard reference source for TeV astronomy, is detected at 15.0 σ. The flux derived from the Milagro data is consistent, within errors, with the flux results obtained from atmospheric Cerenkov telescopes (Aharonian et al. 2004b). The fit location is 0.11° from the pulsar location, which is consistent with the statistical error.

MGRO J2019+37 is one of five Milagro sources in the Cygnus region of the Galactic plane. It is the most significant source detection by Milagro after the Crab and was discussed in depth in Abdo et al. (2007). More data have been analyzed since the publication of that paper, so the flux and significance in Table 2 have been updated.

MGRO J1908+06 is observed with a pretrial significance of 8.3 σ, with a flux that is ~80% of the Crab flux. This location is the closest of the eight candidates to the inner Galaxy, where the diffuse emission is expected to increase. This source is coincident with GeV J1907+0557 and with the bright radio, shell-type, SNR G40.5−0.5 (Green 2006). GeV J1097+0557 was observed for 87 hr by the HEGRA TeV Observatory, resulting in an upper limit for a point source of 2.6% of the Crab flux at 700 GeV (Aharonian et al. 2005b). The Milagro data are consistent both with a point source and with an extended source of diameter up to <2.6°. The Milagro flux and HEGRA upper limit taken together imply a harder spectrum than the ones found in other Galactic sources detected in this energy range by HESS. However, if the source is extended, the HEGRA upper limit would be increased, allowing for a spectrum typical of other TeV sources. The Tibet Air Shower Observatory has a similar energy threshold and angular resolution as Milagro, and reports a location within 0.9° of MGRO J1908+06 as one of eight locations in their survey of the northern hemisphere sky that is above 4.5 σ (Amenomori et al. 2005).

MGRO J2031+41 is observed with a pretrial significance of 6.6 σ and is located in the area with the largest concentration of molecular and atomic gas in the Cygnus region. Its location is consistent with EGRET sources GeV J2035+4214 and 3EG J2033+4118 and with TeV J2032+413 (Aharonian et al. 2005a). The flux of TeV J2032+413 is measured up to ~10 TeV and is only about one-third of the Milagro flux when extrapolated to
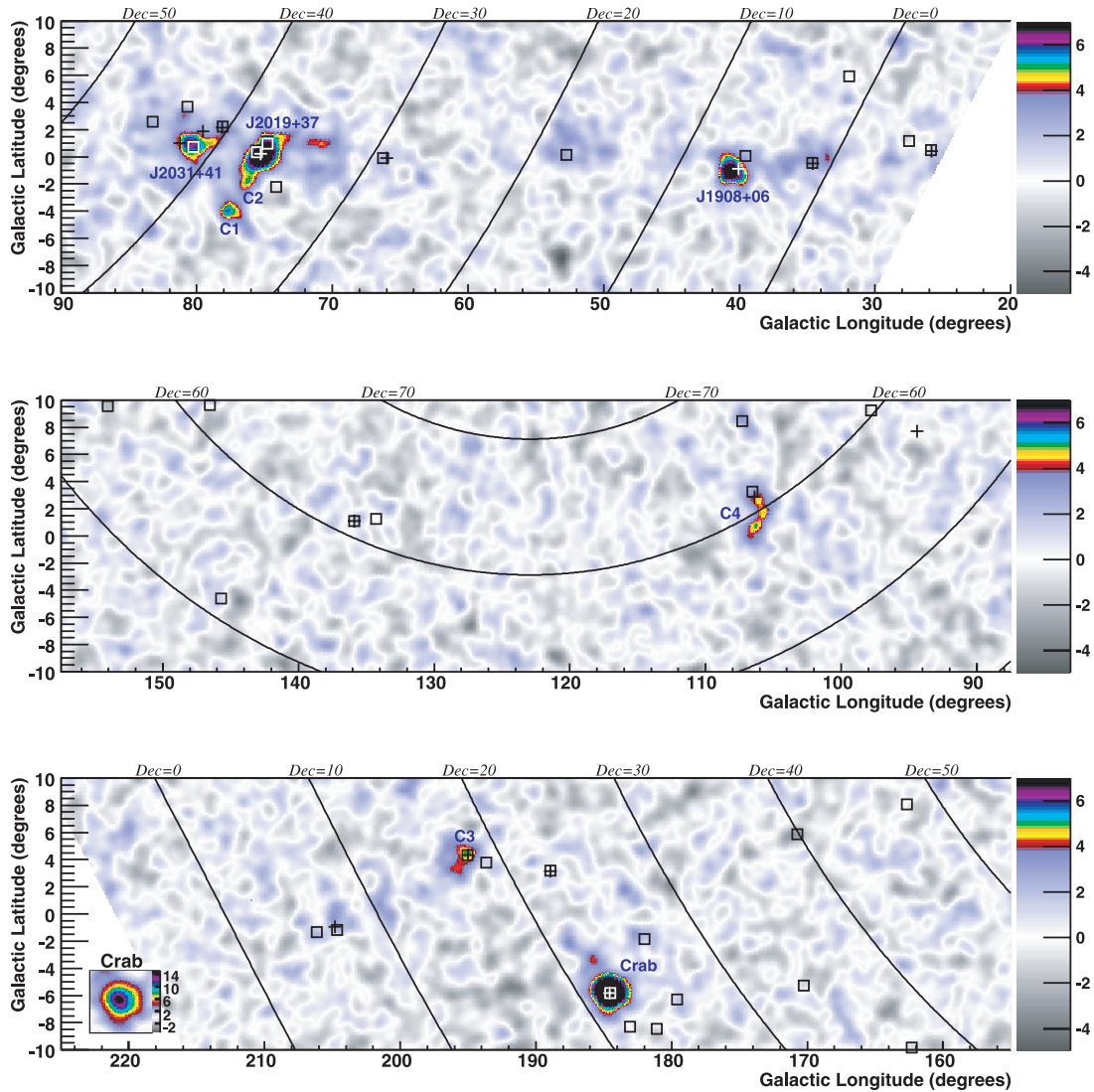
FIG. 1.—Significance map of the Galactic plane. The color code shows the pretrial significance in this PSF-smoothed map. The maximum positive value of the color code saturates at 7 σ, although three of the gamma-ray sources are detected with much higher statistical significance. The Crab image is inset with the same x- and y-scale in the bottom left, as an indication of the PSF. Boxes (crosses) indicate the locations of the EGRET 3EG (GeV) sources.

20 TeV. The low-energy counterpart for TeV J2032+413 is unclear, but several possibilities have recently been postulated (Butt et al. 2006; Anchordoqui et al. 2007). The spatial extent of the Milagro detection, at $3.0° \pm 0.9°$, is much larger than the few arcminute extent of TeV J2032+413. There must be another source or sources contributing to the Milagro excess.

There are two source candidates in the Cygnus region—C1 and C2—that are less significant and have no obvious EGRET, PWN, or SNR counterparts. C1 is located farthest from the Galactic plane at $b = -3.9°$. C2 may be an extension of MGRO J2019+37 but is 2.2° away. C2 is not well fit by a two-dimensional Gaussian. For this source, the bin in the PSF-smoothed map with the highest excess is used to determine the best location, and the flux is obtained from the excess in a $2.0° \times 2.0°$ angular bin.

C3 is positionally consistent with Geminga, which is the brightest EGRET source in the northern hemisphere sky. Geminga is a pulsar that is only 160 pc away and is ~300,000 years old (Caraveo et al. 1996). The 5.1σ source detected by Milagro is consistent with the pulsar location and is extended with a

diameter of $2.8° \pm 0.8°$. The significance increases to 5.9 σ in a $3° \times 3°$ bin. The significance of the Milagro excess at the location of the pulsar is 4.9 σ in the PSF-smoothed map. Only pulsed emission was detected by EGRET, but a PWN has been observed in X-rays (Caraveo et al. 2003) that delineates the bow shock created by the pulsar's motion. The diameter of the excess implies an ~8 pc source extent, which is consistent with the observations by HESS of more distant PWNe (Aharonian et al. 2005c). The upper limits on the TeV flux from Geminga of ~100 mcrab (Aharonian et al. 1999; Akerlof et al. 1993; Vishwanath et al. 1993) were at a lower energy and werebased on the assumption that the emission was from a point source. If the spectral index is ~-2.3 or harder, or if the source is extended, the Milagro detection is consistent with the previously reported limits.

C4 is the least significant source in Table 2 at 5.0 σ. However, as seen in Figure 1, the source appears very elongated, and the significance increases to 6.3 σ with the larger $3° \times 3°$ bin. The source location is consistent with 3EG J2227+6122, GeV

TABLE 2
Galactic Sources and Source Candidates

Object	Location (l, b) (deg)	Error Radius[a] (deg)	Significance (σ)[b]			Flux[c] at 20 TeV (10^{-15} TeV^{-1} cm^{-2} s^{-1})	Extent Diameter (deg)	Possible Counterparts
			Pretrials	Posttrials	3° × 3°			
Crab	184.5, −5.7	0.11	15.0	14.3	11.5	10.9 ± 1.2	...	Crab
MGRO J2019+37	75.0, 0.2	0.19	10.4	9.3	8.5	8.7 ± 1.4	1.1 ± 0.5[d]	GeV J2020+3658, PWN G75.2+0.1
MGRO J1908+06	40.4, −1.0	0.24	8.3	7.0	6.3	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	6.4	9.8 ± 2.9	3.0 ± 0.9	GeV J2035+4214, TeV J2032+413
C1	77.5, −3.9	0.24	5.8	3.8	3.4	3.1 ± 0.6	<2.0 (90% CL)	...
C2	76.1, −1.7	...[e]	5.1	2.8	4.5	3.4 ± 0.8	...[e]	...
C3	195.7, 4.1	0.40	5.1	2.8	5.9	6.9 ± 1.6	2.8 ± 0.8	Geminga
C4	105.8, 2.0	0.52	5.0	2.6	6.3	4.0 ± 1.3	3.4 ± 1.7	GeV J2227+6106, SNR G106.6+2.9

[a] This table lists statistical errors only. The systematic pointing error is <0.3°.
[b] The posttrial significances account for the trials incurred in searching the 3800 deg² region.
[c] This table lists statistical errors only. The systematic flux error is 30%.
[d] For this high-significance detection, the extent was computed using only large events. See Abdo et al. (2007) for details.
[e] Gaussian fit of excess failed for this candidate.

J2227+6106, and the SNR G106.6+2.9 with the accompanying BOOMERANG PWN. This PWN is predicted by Bednarek & Bartosik (2005) to be the third brightest TeV PWN in the northern sky, surpassed only by the Crab and PWN G75.2+0.1, which both have high-significance Milagro counterparts.

4. DISCUSSION

A survey of 190° of the Galactic plane at ~20 TeV has been performed with Milagro with a sensitivity from 3 to 6 × 10^{-15} TeV^{-1} cm^{-2} s^{-1}. Eight sources are identified with >4.5 σ pretrial significance above the isotropic cosmic-ray background. All four of the high-confidence sources and two of the lower significance candidates are associated with EGRET GeV sources, of which there are only 14 in the search region. Four of these six sources appear extended, and the significance of the other two lower significance sources increases substantially with a larger bin of size 3° × 3°. The significance for a true point source would be expected to decrease slowly for larger bin sizes due to the addition of gamma rays beyond the edge of the optimal bin. On the other hand, the significance of a statistical fluctuation would be expected to decrease inversely proportional to the bin radius. The remaining two lower confidence source candidates are within the Cygnus region, where the diffuse emission is high and the concentration of EGRET sources is large.

The differential photon spectrum that connects the fluxes observed by EGRET at 1 GeV with those observed at 20 TeV by Milagro is described by a power law with spectral index $\alpha \sim -2.3$, except for Geminga, which is steeper. This spectrum implies a break from the harder spectra observed for most of these sources by EGRET above 100 MeV. Four of these sources are associated with PWNe, of which only 11 are known in this region (Roberts 2004), and one is associated with a SNR. Other members of these classes of sources have also been detected by HESS. The angular extents of the Milagro sources are large, as would be expected if the sources are nearby, like Geminga.

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