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MILAGRO IN HIGH ENERGY GAMMA-RAY ASTROPHYSICS*

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The gamma-ray emission from the galaxy as visible from the Northern Hemisphere — Galactic latitude $|b| < 10°$ and Galactic longitude $l \in [30°, 216°]$ — is measured at TeV energies by the Milagro Gamma-Ray Observatory. The Milagro experiment performed a survey of this region of the Galaxy and observed eight sources or source candidates with a pre-trials significance of 4.5 standard deviations above the isotropic background. The contribution of these sources is subtracted from the total emission in the studied Galactic plane region to calculate the diffuse flux near the Galactic equator. The flux and position of the eight excess locations, as well as the diffuse emission profiles will be reported.

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Milagro [1] is a water Čherenkov detector at an altitude of 2650 m capable of continuously monitoring the overhead sky. It is composed of a central instrumented 60 m × 80 m pond surrounded with a sparse 200 m × 200 m array of 175 "outrigger" tanks. The pond is instrumented with two layers of photomultiplier tubes. The top "air-shower" layer consists of 450 PMTs under 1.4 m of water while the bottom "muon" layer has 273 PMTs located 6 m below the surface. The air-shower layer allows the accurate measurement of shower particle arrival times used for reconstruction of shower direction and triggering. The greater depth of the muon layer is used to detect penetrating muons and hadrons. The outrigger array improves the angular resolution of the detector by providing a longer lever arm with which to reconstruct events. The angular resolution improves from $\sim 0.75°$ to $\sim 0.45°$ when outriggers are used in the reconstruction. Milagro's large field of view (∼2 sr) and high duty cycle (> 90%) allow it to monitor the entire overhead sky

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continuously, making it well-suited to measuring diffuse emission. The Milagro data, collected between 2000 and 2007, are analyzed using the method described in [2]. Only events with zenith angle less than 45° are included. The event excess is calculated using the background estimation method described in [3] with the modification that each event is now assigned a weight based on the gamma/hadron separation parameter (A_4) [2].

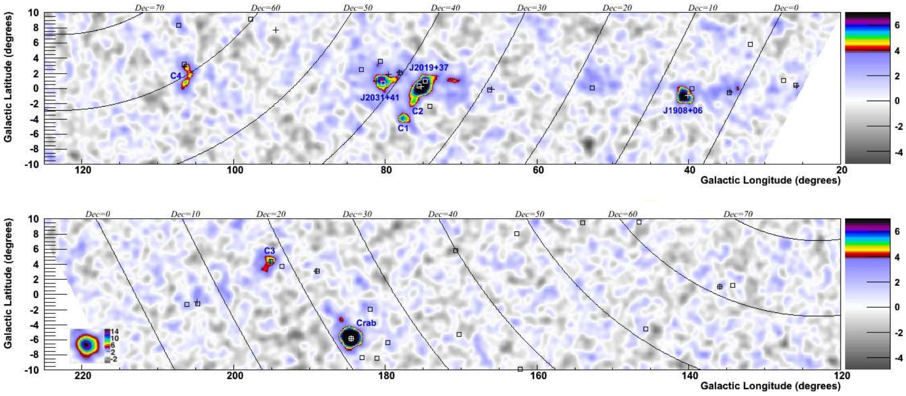

Fig. 1. Milagro significance map of the Galactic plane. Shown are the pre-trials significances. The maximum value of the color code saturates at 7σ, but there are three sources which are detected with higher significance: the Crab Nebula (shown with the unsaturated color code in the lower left corner), MGRO J2019+37, and MGRO J1908+06.

Fig. 1 shows the Milagro map of the Galactic plane, which is smoothed according to the point spread function (PSF) of the experiment. The color scale indicates the statistical significance of the event excess or deficit at each point. The location, statistical significances, and counterparts for the eight source candidates which are identified with a pre-trials significance of $> 4.5\,\sigma$ in the PSF-smoothed map are listed in Table I. The source location was derived first by searching the PSF smoothed Milagro signal map for excesses over the background with a statistical significance of $> 4.5\,\sigma$ and then by fitting the event excess around each source candidate to a two dimensional Gaussian. The error radius listed in Table I is the statistical error from the fitting procedure. The systematic pointing error is $< 0.3°$. The statistical significance of the excess listed in Table I is calculated using Eqn. (17) in Li and Ma [4]. The post-trials significance is computed using a Monte Carlo simulation that accounts for the trials involved in searching a 3800 square degree region. Aside from the Crab Nebula there are three source candidates which exceed $4.5\,\sigma$ after accounting for trials and are thus considered definitive TeV γ-ray source detection. Consult [5] for a more detailed discussion of the sources.

TABLE I

Galactic sources and source candidates observed by Milagro.

Object	Location (l, b)	Error radius (deg)	Signif. (σ) pre-trials	Signif. (σ) post-trials	Possible counterparts
Crab	184,5,−5.7	0.11	15.0	14.3	Crab
MGRO J2019+37	75.0, 0.2	0.19	10.4	9.3	GEV J2020+3658 PWN G75.2+0.1
MGRO J1908+06	40.4, −1.0	0.24	8.3	7.0	GEV J1907+0557 SNR G40.5-0.5 HESS J1908+063
MGRO J2031+41	80.3, −1.1	0.47	6.6	4.9	GEV J2035+4214 TEV J2032+413
C1	77.5, −3.9	0.24	5.9	3.9	—
C2	76.1, −1.7	—	5.1	2.8	—
C3	195.7, 4.1	0.40	5.1	2.8	Geminga
C4	105.8, 2.0	0.52	5.0	2.6	GEV J2227+6106 SNR G106.6+2.9

Diffuse TeV γ-ray emission produced in the interaction of cosmic ray particles with matter and radiation in the Galaxy is also observed by the Milagro experiment and can be used to probe the origin of cosmic rays. Fig. 2 shows the Galactic longitude profile of the γ-ray emission as measured by Milagro and after the event excesses from the above eight Milagro source candidates are subtracted. A γ-ray flux increase towards the Galactic center is visible, as well as the Cygnus region ($l \in [65°, 85°]$) with a distinct "bump" in the flux profile. The data points in Fig. 2 are overlaid with the γ-ray emission profiles as predicted by two incarnations — "conventional" and "optimized" — of GALPROP, a numerical model of propagation of cosmic rays in the Galaxy [6]. As can be seen in Fig. 2, the largest discrepancy between model predictions and data appears in the Cygnus region. The measured diffuse flux from the Cygnus regions is three (seven) times higher than the "optimized" ("conventional") GALPROP prediction. Even though both GALPROP and the Milagro measurements have large systematic uncertainties, the discrepancy between data and model predictions — at least in the Cygnus region — imply the existence of an additional gamma-ray component. Possible explanations for this component include yet unresolved sources, a population of high-energy electrons producing an inverse Compton flux at TeV energies, or a population of dark cosmic-ray accelerators in which the hadrons do not interact near the sources, but instead with the local matter distribution.

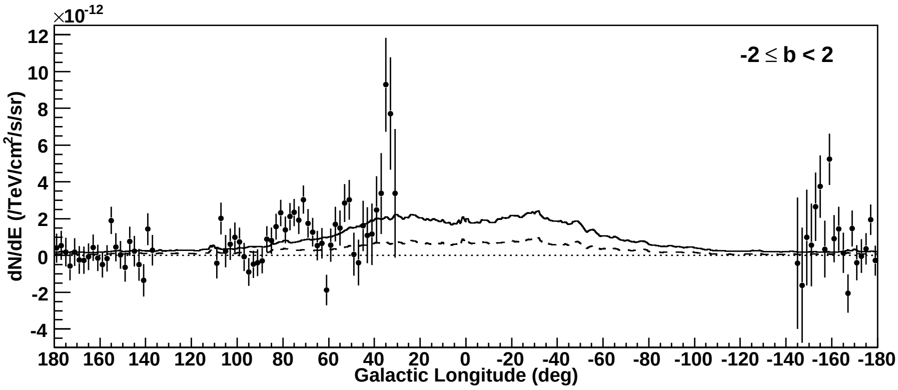

Fig. 2. Source-subtracted Galactic longitude profile of the TeV γ-ray emission in the Galactic plane as measured by Milagro (points) and predicted by GALPROP (solid line: "optimized", dashed line: "conventional").

Experiments like the proposed High Altitude Water Čherenkov (HAWC) detector, will be able to constantly survey large regions of the sky, in particular of the Galactic plane, at TeV energies with 10 to 15 times the sensitivity of Milagro. HAWC will hopefully shed light on the situation and produce results that will put stricter constraints on theoretical models like GALPROP and thus provide crucial information about the propagation of cosmic rays above about 100 TeV.

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