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Detection of TeV Gamma Ray Emission from the Galactic Plane

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Diffuse gamma rays produced by interactions of cosmic rays with matter in the Galaxy have previously been detected up to 30 GeV by the EGRET instrument. Here we report the first detection of a TeV gamma-ray flux from the Galactic plane by Milagro. An excess with a significance of 4.5 standard deviations is observed from a region of Galactic longitude $l \in (40^o, 100^o)$ and latitude $|b|<5^o$. The measured integral gamma-ray flux is $\phi(>3.5\ \mathrm{TeV}) = (6.4 \pm 1.4 \pm 2.1) \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$. This flux is consistent with an extrapolation of the EGRET spectrum between 1 and 30 GeV in this region of the Galaxy.

1. Introduction

Cosmic ray interactions with ambient material in the Galaxy produce gamma rays. The flux and spectrum of these gamma rays tells us the importance of the several possible mechanisms for gamma-ray production – π^o decay, electron bremsstrahlung, and inverse Compton scattering of high-energy electrons with the interstellar radiation field. The EGRET instrument [1] measured an excess of gamma rays in a narrow band around the Galactic equator over values predicted based solely on π^0 production above 1 GeV. In addition the differential spectral index measured by EGRET at these energies was $\alpha \approx -2.3$, significantly harder than the cosmic-ray spectrum.

Milagro [2,3] is a large field-of-view (~2 sr) cosmic gamma-ray detector that is sensitive to TeV gamma rays. Milagro consists of a large water reservoir ($\sim 2.4 \times 10^7$ liters), instrumented with two layers of photomultiplier tubes (PMTs). The top layer of 450 PMTs is situated under ~1.4 m of water on a 2.7 m square grid. The bottom layer of 273 PMTs is under ~6 m of water and also on a 2.7 m square grid. The direction of the primary gamma ray (or cosmic ray) is obtained by fitting the corrected arrival times of the air shower particles (as detected in the top layer of PMTs) to a plane. The resulting angular resolution is roughly 0.75^o. The bottom layer of PMTs is used to detect the penetrating component (muons and showering hadrons) of air showers produced by hadronic cosmic rays. A "compactness" cut [3] rejects roughly 90% of the cosmic-ray background while retaining roughly 45% of the gamma-ray signal. In addition to the compactness requirement in the subsequent analysis we have also required:

1. At least 50 PMTs in the top layer be struck
2. At least 20 top layer PMTs must be used in the angular reconstruction
3. Zenith angle of the event must be <50 degrees
4. The declination of the event must be between 10 and 60 degrees.

2. Data Analysis

Here we present the analysis of 3 years of data beginning in July of 2000. While EGRET measured the greatest flux from a region near the Galactic center, this region is not visible to Milagro (latitude of 36 degrees). There are two regions of the Galaxy for which we have good (and roughly equal) exposure: R1 spans the Galactic longitude range from 40 degrees to 100 degrees (which includes the Cygnus region) and R2 which spans the longitude range from 140 to 200 degrees. Based upon the flux measurements made by

EGRET we expect that the flux (and significance) from R1 will be twice that in R2. Based upon the EGRET detection we chose a latitude band of ±5 degrees about the Galactic equator for both regions.

The background estimation is performed utilizing the data to parameterize the response of the detector as a function of local coordinates and then by using the events as an "integration grid" for this response function we naturally compensate for any rate changes in the detector. The exact method used here is slightly different than that described in [3,4]. In those papers it was assumed that the detector response function (in local coordinates) was constant over each integration time period (2-hours in [3]). Because of the large sizes of R1 and R2 here we use an 8-hour integration period to measure the detector response. During each 8-hour interval we observe a slight change in the zenith angle distribution of events. This change is parameterized and a correction is applied to the background estimation as described in [5]. Finally a small anisotropy was observed in the incident cosmic ray arrival directions. The phase and amplitude of this anisotropy are similar to those seen by the Tibet array [6]. The final background estimate is corrected for this anisotropy. For R1 the correction is $\delta = (-0.63 \pm 0.30) \times 10^{-4}$ and for R2 $\delta = (+0.04 \pm 0.30) \times 10^{-4}$. Table 1 gives the results of this analysis. After correcting for the cosmic-ray anisotropy there is a 4.5 standard deviation excess observed in R1 and slight deficit in R2. In Figure 1 we show a map of the Northern hemisphere is Galactic coordinates as observed in TeV gamma rays. At each location (a 5x5 degree bin on the sky) the significance of the observed excess/deficit is given by the color code. Note that R1 is the most significant region in the region of the sky observed by Milagro.

Table 1. Results of the analysis for R1 and R2. N_s is the number of signal events and N_b is the background estimate (uncorrected for the observed cosmic-ray anisotropy). F_{raw} is the observed fractional excess, δ is the correction to the excess due to the cosmic-ray anisotropy, and F is the actual fractional excess after correcting for the cosmic-ray anisotropy.

	Region R1	Region R2
N_s	238,095,657 ± 15430	254,800,416 ± 15962
N_b	238,025,840 ± 8003	254,826,272 ± 8841
N_s-N_b	69,817 ± 17382	-25,853 ± 18247
F_{raw}	$(2.93 \pm 0.73) \times 10^{-4}$	$(-1.01 \pm 0.72) \times 10^{-4}$
δ	$(-0.63 \pm 0.30) \times 10^{-4}$	$(0.04 \pm 0.30) \times 10^{-4}$
F	$(3.56 \pm 0.79) \times 10^{-4}$	$(-1.05 \pm 0.78) \times 10^{-4}$

3. Discussion

To convert the fractional excess to a gamma-ray flux we use Monte Carlo simulations of proton and helium cosmic rays and gamma rays to determine the relative sensitivity of Milagro to each of these particles. This relative sensitivity is normalized by the measured rate and spectrum of cosmic protons and helium nuclei to yield the gamma-ray flux. The flux above 3.5 TeV of H and He is taken from [7] to be $\phi_{H+He} = 1.2\times10^{-6}$ cm^{-2} sec^{-1} sr^{-1}. Because this data set preceded the construction of an array of water tanks that currently surround Milagro, individual event energies were not available for this analysis. Since the effective area of Milagro is dependent upon the gamma-ray energy the determination of the flux and the spectral index are correlated. In this analysis we use the highest energy EGRET measurement (10-30 GeV) to help constrain the fit parameters. The resulting best fit values for the flux and differential spectral index are: $\phi_\gamma(>3.5 \text{ TeV}) = (6.8 \pm 1.3 \pm 2.3) \times 10^{-11}$ cm^{-2} sec^{-1} sr^{-1} and $\alpha_\gamma = 2.61 \pm 0.03 \pm 0.06$. A fit to the four highest EGRET energy measurements (1-30 GeV) in R1 [8] yields a differential spectral index of $\alpha_{\gamma(\mathrm{EGRET})} = 2.51 \pm 0.05$, consistent with the above result from Milagro and the highest energy EGRET data point. For R2 we report a 99% c.l. upper limit to the flux of $\phi_\gamma(>3.5 \text{ TeV}) < 5.0 \times 10^{-11}$ cm^{-2} sec^{-1} sr^{-1}. Figure 2 gives the Milagro measurement in R1 and the upper limit in R2 along with the extrapolation from the highest four EGRET data points.

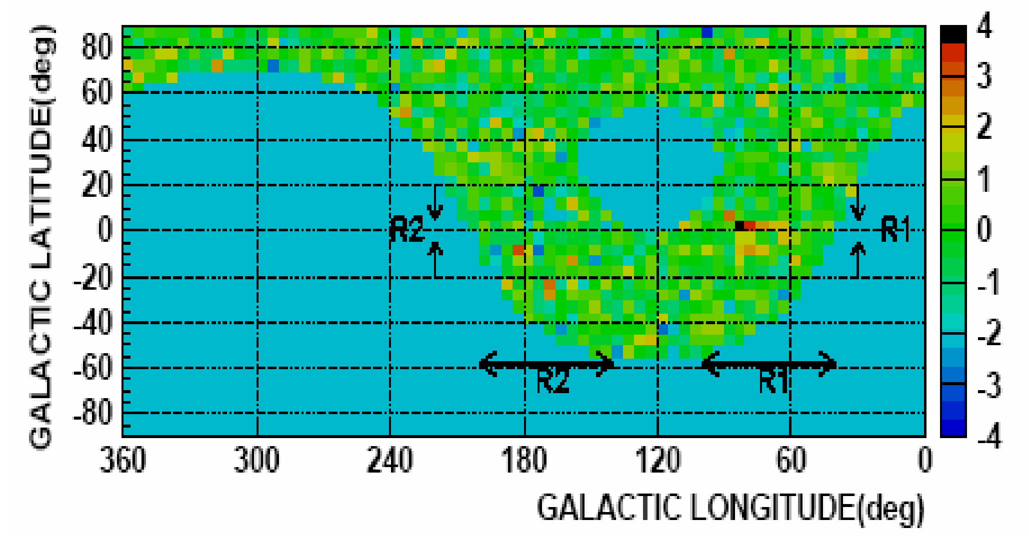

Figure 1. The Northern hemisphere in TeV gamma rays shown in Galactic coordinates. The sky was divided into independent 5x5 degree bins, at each location the significance of the observed excess or deficit is given by the color scale. R1 is the brightest region of the sky. The next brightest bin in this analysis contains the Crab Nebula (near l=180, b=-10).

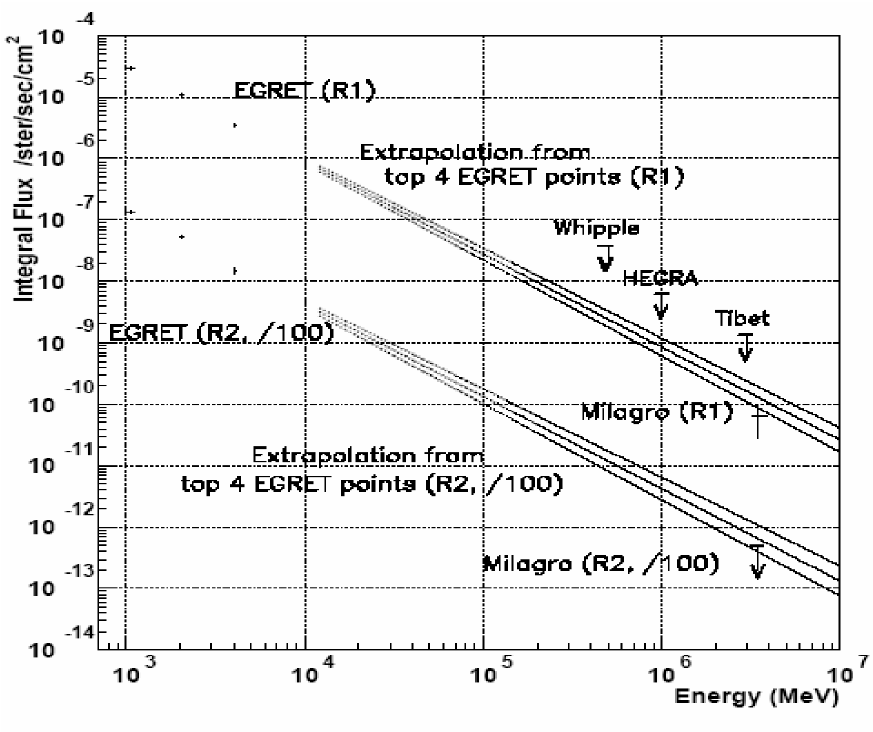

Figure 2. Integral flux results of Milagro and EGRET, with the 99% c.l. upper limits from Whipple[9], HEGRA[10], and Tibet[11]. For R2 the results are multiplied by 0.01 for clarity**.**

Milagro has made the highest energy measurement of the flux of gamma rays from the Galactic plane. This flux most likely has several components at least one of which is due to the interaction of cosmic rays with matter in the Galaxy. Unresolved point sources may also contribute to this flux. If there is no cutoff in the gamma-ray flux below 10 TeV than these results are consistent with a gamma-ray power law index that asymptotically approaches the cosmic-ray spectrum as predicted if π^0 production is becomes the major source of the gamma-ray flux [12].

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