Study of galactic gamma ray sources with Milagro

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Abstract. The diffuse gamma radiation arising from the interaction of cosmic ray particles with matter and radiation in the Galaxy is one of the few probes available to study the origin of the cosmic rays. Milagro is a water Cherenkov detector that continuously views the entire overhead sky. The large field-of-view 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 diffuse gamma radiation arising from interactions of cosmic radiation with interstellar matter. In this paper we report our results on diffuse emission from the galactic plane and in particular the Cygnus region. Our observations show at least one new TeV source MGRO J2020+37 as well as correlations with the matter density in the region as would be expected from cosmic-ray proton interactions. However, the TeV gamma-ray flux from the Cygnus region (after excluding MGRO J2020+37) is roughly 5 times that expected from a conventional model of cosmic ray production and propagation.

1. Introduction

Milagro is the first large area, continuously operating, water Cherenkov detector used for gamma-ray astronomy. Milagro consists of a 24 million liter water reservoir instrumented with 723 photomultiplier tubes (PMTs) surrounded by an array of 175 water tanks. The top layer of 450 PMTs is beneath 1.3 meters of water and is used to trigger the detector and to reconstruct the direction of the primary gamma ray (or cosmic ray). The bottom layer of 273 PMTs is beneath 6 meters of water and is used to measure the penetrating component of air showers induced by hadronic cosmic rays. The PMT spacing in the reservoir is 2.7 meters and the area enclosed is 4800 m^2. The surrounding array of water tanks is dispersed over 34,000 m^2. Each tank is cylindrical with a 1.6 meter radius and a depth of 1 meter. The tanks are instrumented with a single PMT located at the top of the tank looking down into the water volume. Milagro began physics operation in 2000 taking data with the central water reservoir. In 2004 construction of the outrigger array was completed. Before the installation of the outriggers the small size of the water reservoir limited the sensitivity of Milagro such that the Crab Nebula was observed at ~4σ in one year of operation. The completion of the outriggers enabled a large increase in the sensitivity of the instrument, enabling us to detect the Crab Nebula at over 8 standard deviations in a single year of observation. This factor of ~2 increase in sensitivity (as shown in figure 1) has dramatically changed our view of the high-energy sky. It also means that the data currently being taken now with Milagro is substantially more important than our original data and we are not simply increasing our sensitivity by the square root of time over a 6-year observational period.

To date our most important observational results with Milagro have been: the first detection of TeV gamma rays from the Galactic plane [1], the mapping of the diffuse Galactic gamma-ray emission at TeV energies, including the detection of the Cygnus Region at high-significance (over 10σ) [2] , the discovery of a new (slightly extended) source of TeV gamma rays embedded in the Cygnus Region [3], and the possible detection of a gamma-ray burst with our prototype instrument Milagrito [4]. In addition, we have detected TeV gamma rays from the active galaxy Mrk 501 [5], Mrk 421 [6] and the Crab Nebula [7], set stringent upper limits on the prompt TeV emission from several gamma ray bursts [8], and performed the most sensitive survey of the northern hemisphere at TeV energies [9].

2. Survey of the Northern Hemisphere

The sensitivity of Milagro has been dramatically improved with the addition of the outrigger array. The effect of this gain in sensitivity is best demonstrated by comparing the results of our published sky survey [10] which used approximately 1000 days of data (top of figure 1) and our current data set of just over 2000 days of data (bottom of figure 1). While both the Crab Nebula and the active galaxy Mrk421 are visible in the top panel, the improvement since the outriggers is dramatic. The significance of the Crab Nebula has increased from 6σ to 14σ and the Galactic plane is now clearly visible, even in this broad map. Our current sensitivity is ~8σ per year for a 1 Crab flux.

3. The Cygnus Region and the Discovery of a TeV γ-ray Source

In 2005, we published the first detection of diffuse TeV gamma-ray emission from the inner Galaxy [11]. The flux of the Milagro detection is not consistent with expectations from cosmic ray interactions if the local cosmic ray flux is indicative of the flux in the rest of the galaxy. There are several possible explanations for this excess: the local cosmic ray flux is unusually low, the local spectral index is soft relative to the rest of the Galaxy, and the existence of unresolved point sources. With the more recent data, taken since the completion of the outriggers, we have refined the analysis to investigate the Cygnus Region of the Galaxy in more detail. The Cygnus Region of the Galaxy is a natural laboratory for the study of cosmic ray origins. It contains a large column density of interstellar gas that should lead to strong emission of diffuse gamma rays and is also the home of potential cosmic-ray acceleration sites (Wolf-Rayet stars [12], OB associations [13], and supernova remnants [14]). Figure 2 shows a detailed view of the Cygnus Region in TeV gamma rays. Superimposed on the figure are contour lines indicating the matter density in the region and the location (and location

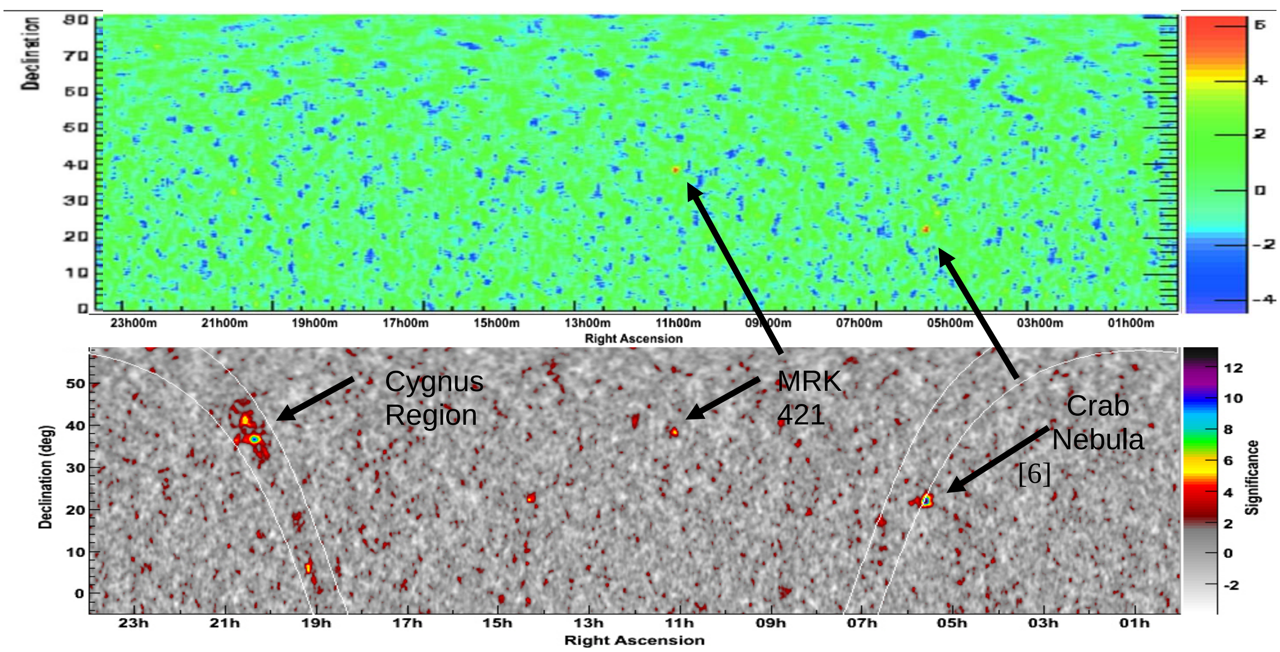

Figure 1. A northern sky seen in TeV gamma rays using Milagro data. The top panel shows the sky as observed before the outriggers and the bottom panel after the completion of the outrigger array.

errors) of the EGRET sources (all unidentified) in the region. There is definitive evidence for a new source of TeV gamma rays (MGRO J2019+37). MGRO J2019+37 is detected at over 10 standard deviations and its location is consistent with the location of two EGRET sources – one of which has been tentatively identified with a pulsar wind nebula [15]. Though it is not evident from this figure, this source is most likely extended with a width of 0.32±0.12 degrees. The best-fit location of this source is R.A.=304.83° $\pm 0.14^{o}_{stat} \pm 0.3^{o}_{sys}$ and Dec.= 36.83° $\pm 0.08^{o}_{stat} \pm 0.25^{o}_{sys}$. Assuming a differential source spectrum of $E^{-2.6}$, the Milagro flux measurement at the median energy of 12 TeV is given by E^2 dN/dE = $(3.49 \pm 0.47_{stat} \pm 1.05_{sys}) \times 10^{-12}$ TeV cm^{-2} s^{-1}. A change in the assumed source spectral index from -2.6 to -2.7 changes the integral flux above 12 TeV by less than 7%.

Figure 3 shows the profiles in latitude and longitude of the inner Galaxy (from 34-120 degrees in Galactic longitude). The median energy of the detected gamma rays is ~12 TeV. It can be seen that the plane has a width of ~±2.5° in latitude. The longitude profile shows a large excess in the Cygnus region as well as an increasing flux towards the Galactic center, however with larger error bars because of the limited view of the Galactic center from the latitude of Milagro.

The flux of diffuse emission from the Cygnus Region is measured after subtraction of the contribution from MGRO 2019+37. Using the GALPROP [16] program we estimate the expected flux of diffuse gamma rays. This estimate has contributions from a pion component arising from the interactions of cosmic rays with matter in the region and from gamma rays produced by inverse Compton interactions of cosmic-ray electrons with infrared radiation in the region. We find that the TeV gamma ray flux is about a factor of 5 larger than that predicted by this standard model of cosmic ray production in the Galaxy. These results are shown in figure 4. The same reference [16] gives a model that explains the GeV excess that can also explain the TeV excess – however, at energies near 10 TeV it implies that the inverse Compton component is dominant and the inverse Compton component would not show such a strong correlation with the matter density. Other plausible explanations of this observation are that the Cygnus region contains cosmic-ray accelerators – thereby increasing the cosmic-ray density in that region relative to the model predictions of GALPROP.

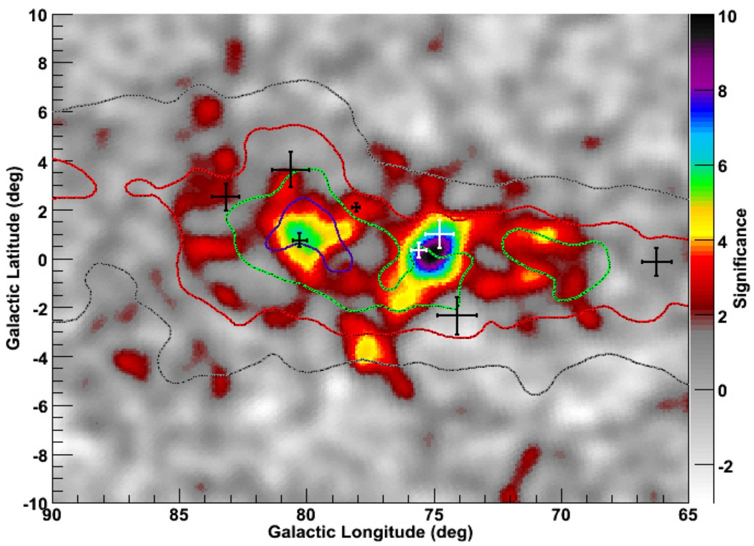

Figure 2 - The Cygnus Region of the Galaxy as seen in TeV gamma rays. Superimposed on the image are contours showing the matter density in the region. The crosses show the location of the EGRET sources and their corresponding location errors.

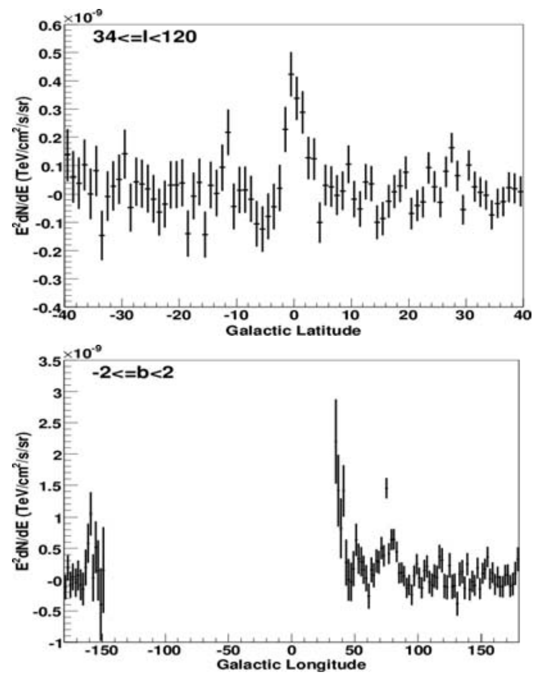

Figure 3. The top figure shows a latitude scan of the Galactic plane in 1 degree bins for the inner Galaxy. The lower figure is a longitude scan in 2 deg bins of ± 2 deg around the Galactic plane.

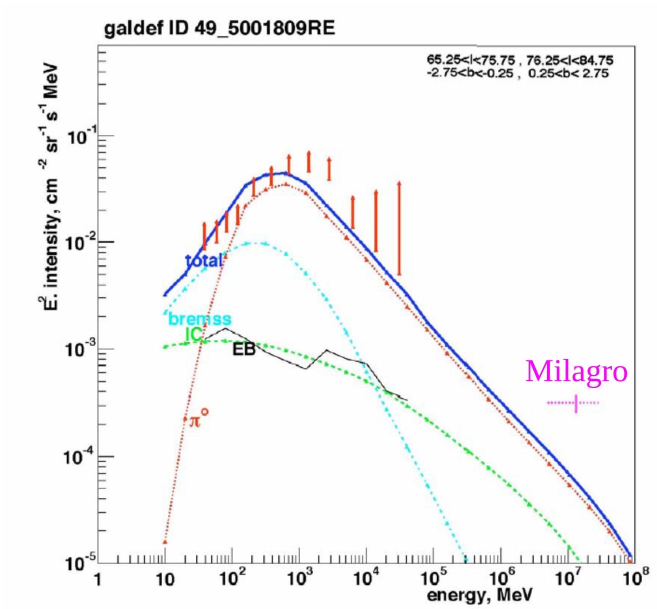

Figure 4. GeV to TeV gamma-ray spectrum of the diffuse emission from the Cygnus Region of the Galaxy. The red bars are the EGRET data and the magenta bar is the Milagro measurement with the statistical error shown. The other lines represent the different components of the emission according to the conventional model (cosmic-ray spectrum and intensity as measured at Earth) of Strong and Moskalenko [16]. The solid blue line is the total predicted diffuse flux, the red line is the pion component, the green line is the component arising from inverse Compton interactions of high-energy electrons with optical and far infrared photons, the light blue line is due to proton bremsstrahlung, and the black line due to the extra galactic background.

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