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Cosmic-Ray Physics with the Milagro Gamma-Ray Observatory

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The Milagro gamma-ray observatory is a water Cherenkov detector with an energy response between 100 GeV and 100 TeV. While the major scientific goals of Milagro were to detect and study cosmic sources of TeV gamma rays, Milagro has made measurements important to furthering our understanding of the cosmic radiation that pervades our Galaxy. Milagro has made the first measurement of the Galactic diffuse emission in the TeV energy band. In the Cygnus Region we measure a flux ~2.7 times that predicted by GALPROP. Milagro has also made measurements of the anisotropy of the arrival directions of the local cosmic radiation. On large scales the measurements made by Milagro agree with those previously reported by the Tibet ASγ array. However, we have also discovered a time dependence to this anisotropy, perhaps due to solar modulation. On smaller scales, ~10 degrees, we have detected two regions of excess. These excesses have a spectrum that is inconsistent with the local cosmic-ray spectrum.

KEYWORDS: cosmic ray, gamma ray

1. The Milagro Detector

The Milagro gamma-ray observatory is located at an altitude of 2630 m above sea level and consists of a central water reservoir covering an area of ~4000 m^2, surrounded by an array of 175 water tanks covering an area of ~34,000 m^2 (the outrigger array). The central detector has dimesions 80m x 50m with a depth of 8m at the center. The reservoir is instrumented with 750 20cm photomultiplier tubes (PMTs) arranged in two layers. The top layer of 450 PMTs is under 1.4 meters of water and the bottom layer of 273 PMTs is under 6m of water. Both layers are on a 2.8m x 2.8m grid. The entire reservoir is enclosed with a light-tight cover. Each water tank has an area of 8m^2 and a depth of ~1m. They are instrumented with a single PMT that is mounted at the top looking down into a TYVEK lined water volume. The PMTs in the top layer and the outrigger array are used to reconstruct the direction of the primary gamma ray (or cosmic ray) to an accuracy of ~0.5 degrees. The bottom layer is used to discriminate against the background cosmic radiation. Air showers induced by hadrons contain a penetrating component (muons and hadrons that shower in the reservoir). This component results in a compact bright region in the bottom layer of PMTs (see[1] for details). A cut based on the distribution of light in the bottom layer removes 92% of the background cosmic rays while retaining 50% of the gamma ray events.[2] The trigger rate (before background rejection) is ~1700 Hz. Milagro began operations in January of 2000, the outrigger array was completed in May 2003, and Milagro ceased operations in April of 2007.

2. Diffuse TeV Gamma-Ray Emission

Figure 1 shows a ±10 degree region around the Galactic plane as seen at ~20 TeV with Milagro. In addition to the point and extended sources detected[3] one can discern the presence of a diffuse gamma-ray flux from the Galaxy, especially near the Cygnus Region and at lower Galactic longitude (near MGRO J1908+06). This diffuse emission is expected to be due to the interaction of cosmic-ray nuclei with matter and inverse Compton interactions of high-energy electrons with lower energy (infrared, optical, and cosmic microwave background) photons. Thus, the measurement of the diffuse gamma-ray emission from our Galaxy yields information about the intensity and spectrum of cosmic ray protons and electrons throughout the Galaxy. Lower energy measurements by the EGRET showed clear evidence of an excess (over predictions based upon the measured matter density and the local cosmic-ray intensity and spectrum) above 1 GeV.[4] Explanations of this GeV excess range from the annihilation of dark matter particles[5] to a varying cosmic-ray spectrum and/or intensity across the Galaxy.[6–8] A model has been developed (GALPROP[6]) to predict the diffuse gamma-ray emission throughout the Galaxy, the model is based upon the matter density, the interstellar radiation field, and the cosmic-ray spectra of protons, electrons, and heavy elements. To account for the GeV excess an "optimized" model was developed where the contribution from the inverse Compton component was increased. (The original GALPROP model is referred to as the conventional model below.) While this increase is relatively small at GeV energies, it predicts that at TeV energies the inverse Compton component dominates over the pion component. (The pion component arises from the interaction of hadronic cosmic rays with matter.) Since ~100 TeV electrons have a relatively short path length, this interpretation implies that measurements of the diffuse gamma radiation at 10 TeV can be used to measure the ~100 TeV electron spectrum at distant locations throughout the Galaxy.

Figure 2[9] shows the diffuse TeV gamma-ray flux and the predictions of both the optimized and conventional GALPROP models. The median energy of the Milagro detection is 20 TeV. The data shown in the figure have had the contributions from the sources discussed in[3] above removed, and thus represent the diffuse flux (in the absence of other as yet unresolved sources). Note that even the optimized version of GALPROP under predicts the TeV flux by a factor of 2.7 in the Cygnus Region. The excess above the GALPROP prediction has a statistical significance of roughly 3 standard deviations. This excess could be explained by the existence of a cosmic-ray accelerator within the Cygnus Region, which would lead to a harder spectrum of cosmic rays within this region and therefore a larger flux of high-energy gamma rays. This explanation is interesting in light of the recent results from the ACE CRIS instrument.[10] This direct measurement of the isotopic abundances of the local cosmic rays at lower energies (~100 MeV/nucleon), indicates that roughly 20% of the Galactic cosmic rays originate from Wolf-Rayet stars (typically found in OB associations). Alternatively, the excess could be explained by unresolved point sources of TeV gamma rays that may lie within the Cygnus Region. The resolution of this question awaits follow-up observations by the VERITAS gamma-ray telescope, which should have the sensitivity to detect as yet unresolved gamma-ray sources (though a measurement of the diffuse emission in this region will be difficult for VERITAS).

3. Anisotropy of the Cosmic Radiation

While several groups have previously reported measurements of cosmic-ray anisotropy (see[11] for a review), these measurements have been one-dimensional, i.e. anisotropy as a function of right ascension. Recently, this situation has changed and current experiments have the statistical power to make quasi-2-dimensional maps of the anisotropy of cosmic rays in the energy range from 1-100 TeV. (The maps are not truly 2-dimensional since they do not have the ability to measure a declination dependent anisotropy. instead they are a series of 1-dimensional maps that give the anisotropy as a function of right ascension versus declination. This is due to the fact that, to date, the data analyses have relied upon the rotation of the earth to determine the relative response of the instruments as a function of local coordinates.[12]) The Tibet ASγ observatory has produced the first such map.[13] Using a completely new analysis technique Milagro has produced a very similar map,[14, 15] Figure 3. There are two striking features of this map: the large deficit near a right ascension of 180 degrees and the excess between right ascension 50 and 70 degrees. The cosmic-ray intensity in the region of the deficit is 0.997 that of the average cosmic-ray intensity and in the region of the excess about 1.002 times that of the average cosmic-ray intensity. The direction of the deficit is the direction perpendicular to the Galactic plane. The direction of the excess near a right ascension of 50 degrees is consistent with the "tail-in" region of the heliosphere, the direction of open magnetic field lines (opposite to the direction of motion of the Sun through the local interstellar medium).

Milagro has also observed that the amplitude of the anisotropy is time-dependent (the phase of the anisotropy does not change with time). Figure 4 shows the amplitude of the anisotropy as a function of the year of the observation. It should be noted that the beginning of the observations (2000) was during solar maximum and the end of the observations (2007) occurred during solar minimum. This observation implies that the more recent data represent the true amplitude of the anisotropy of the Galactic cosmic rays. At energies near 1 TeV the heliosphere can affect the propagation of cosmic rays,[16, 17] though at much higher energies one does not expect an influence from the heliosphere. Milagro has also measured the energy dependence of the anisotropy and find that the amplitude is a maximum near 4 TeV and persists to at least 100 TeV. The anisotropy at the higher energies may be due to the distribution of nearby (<1 kpc) young (<50 kyr) supernova remnants and the diffusion of cosmic rays.[18, 19]

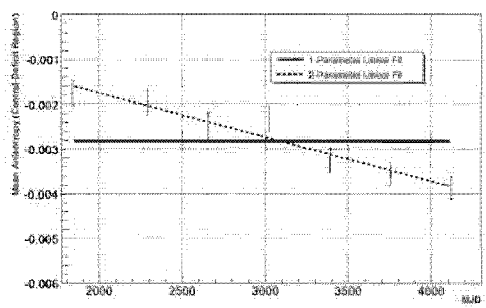

Fig. 4. The amplitude of the large scale anisotropy in the cosmic radiation as a function of modified Julian date minus 50,000. The data was taken with the Milagro detector. An x-axis label of 2000 corresponds to April 1, 2001 and the label 4000 is September 22, 2006.

A search for intermediate scale anisotropy has uncovered several puzzling features. A 2-dimensional plot of the intermediate scale anisotropy of the cosmic radiation is shown in Figure 5.[20] The smoothing scale for this analysis was 10 degrees. There are two notable localized excesses: Region A, near a right ascension of 70 degrees, and region B, the large arc near a right ascension of 130 degrees. With its ability to distinguish gamma-ray induced EAS from hadronic EAS,[1] the Milagro data have been used to conclusively demonstrate the hadronic nature of these excesses.[20] A coarse estimate of the energy spectrum of Region A has been made using the Milagro data. The energy of the primary cosmic ray is well correlated (though with large rms) with the fraction of the outrigger tanks struck. In Figure 6, we show the average energy as a function of the natural logarithm of the fraction of outrigger tanks struck and the distribution of this parameter for the excess in Region A. While Region B is consistent with the cosmic-ray spectrum, the excess in Region A has a harder spectrum than the cosmic-ray background (at the 4.6 standard deviation level) and disappears above about 10 TeV. Given that the Larmor radius of a 10 TeV proton in the local magnetic field, 2μGauss,[21] is roughly 0.005 pc and the decay length of a 10 TeV neutron is only 0.1 pc, it is difficult to under-

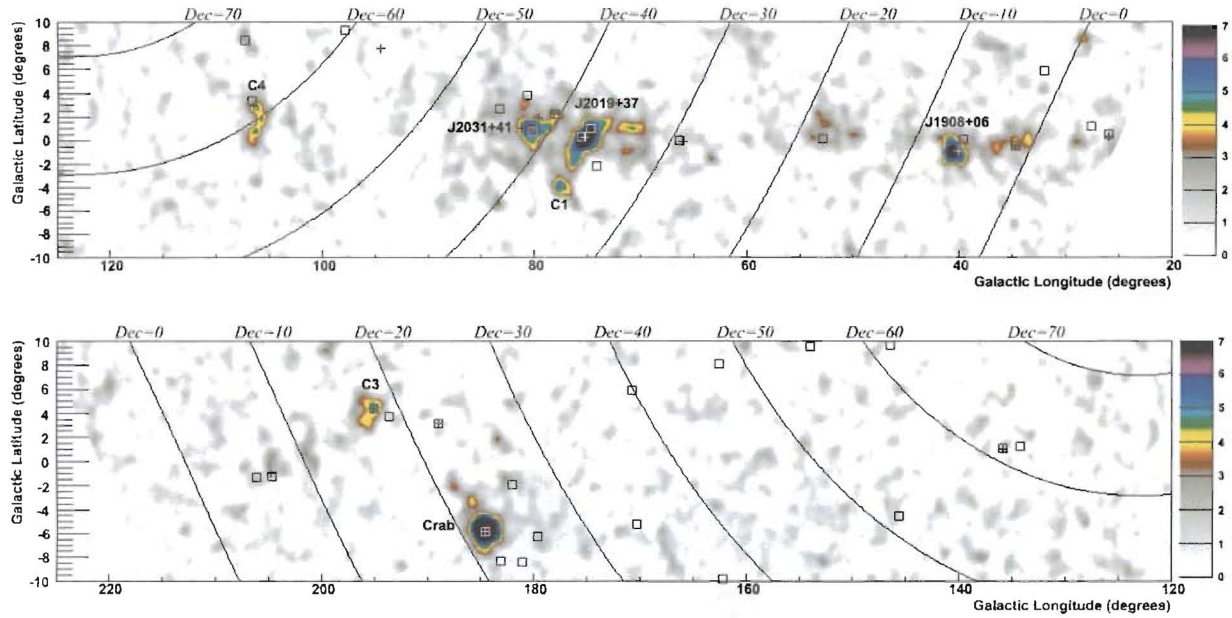

Fig. 1. The Galaxy in TeV gamma rays from Galactic longitude 20 degrees to 220 degrees and Galactic latitude from -10 degrees to 10 degrees. The image is the culmination of a seven year exposure by the Milagro instrument. The color scale shows the statistical significance of the observed excess (over the cosmic-ray background) at each point. Crosses mark the location of GeV sources and boxes mark the location of sources in the 3EG catalog. Locations marked as C1,C3, & C4 are candidate sources as determined by Milagro and the three locations marked as JXXXX+YY are sources discovered by Milagro. To improve the clarity of the figure significances above 7 standard deviations are shown as black and those below 3 standard deviations are shown as a monochrome.

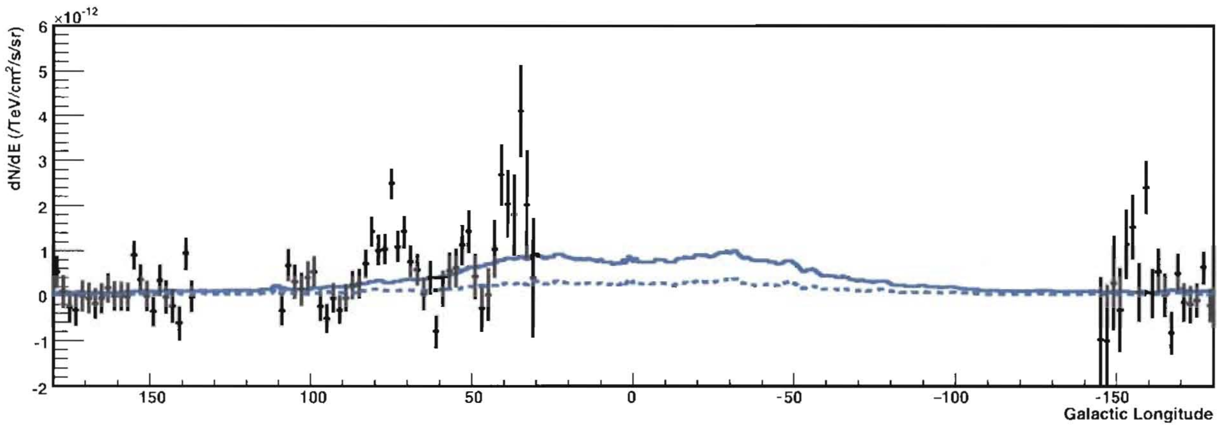

Fig. 2. The longitudinal profile of the Galactic diffuse emission of TeV gamma rays measured by the Milagro observatory.[9] The solid line shows the prediction of the "optimized" GALPROP model (increased inverse Compton component to fit EGRET data) and the dashed line shows the prediction of the "conventional" GALPROP model (cosmic-ray intensity and spectrum assumed to be the same as measured at earth). Note that even the optimized model under predicts the TeV measurement in the Cygnus Region.

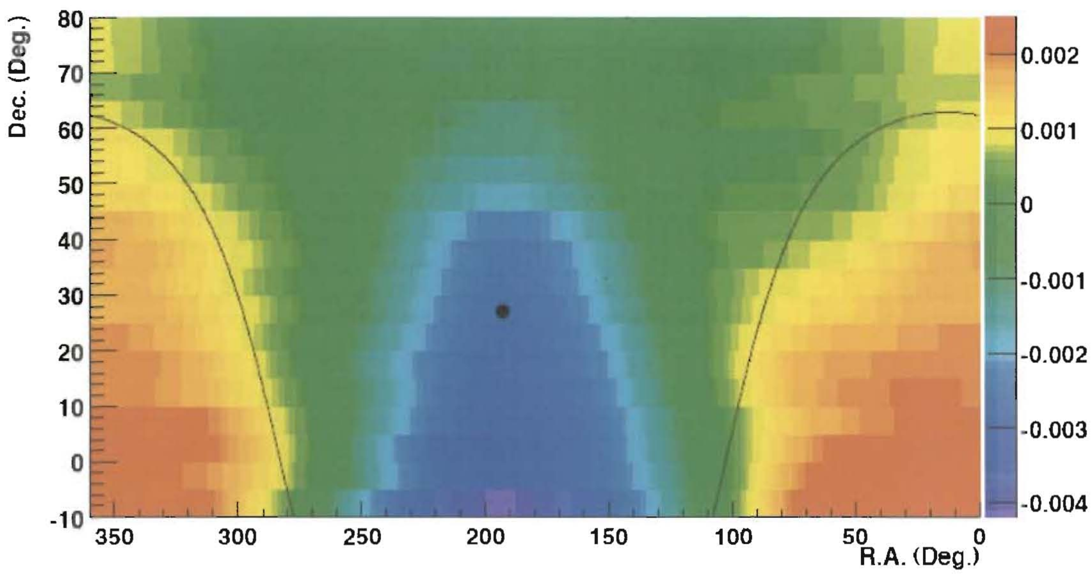

Fig. 3. The anisotropy in the cosmic radiation as measured by the Milagro observatory. Shown is the fractional excess as a function of right ascension and declination. This map is very similar in appearance to the map from th Tibet ASγ detector.[13] Region III is the Cygnus Region and the observed excess in that direction is consistent with the gamma-ray flux measured by Milagro in that direction.

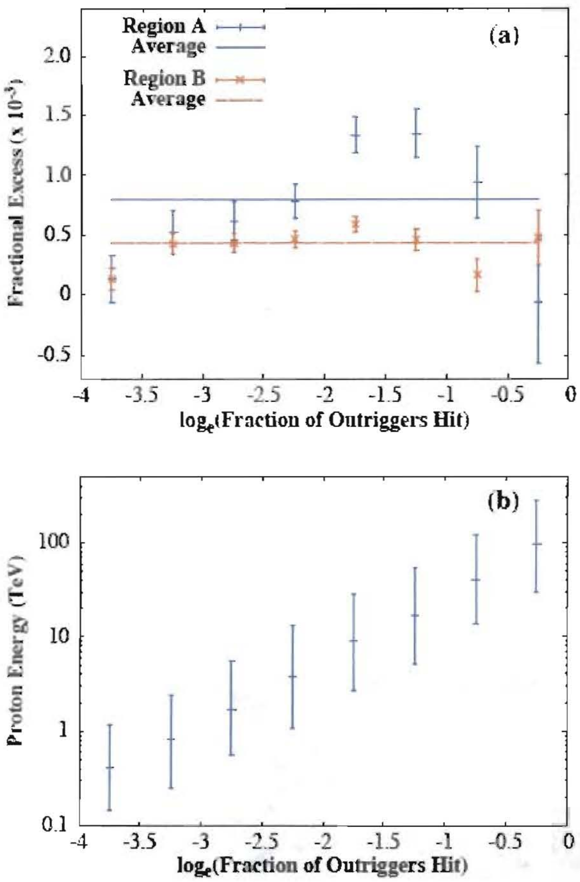

Fig. 6. (a) the distribution of the fractional excess of Regions A and B as a function of the natural logarithm of the fraction of the outriggers struck. The horizontal line represents the cosmic-ray spectrum (i.e. the excess is independent of the energy). (b) The average proton energy as a function of the natural logarithm of the fraction of the number of outriggers struck. The error bars contain 68% of the events. The probability that the distribution from Region A came from a horizontal line is 2×10^{-6}.

stand the phenomena that may be the cause of the observed excesses, though several explanations have been proposed.[22,23]

4. Future Directions

Based upon the success of both the water Cherenkov technique (as demonstrated by Milagro) and the advantages of siting an extensive air shower array at high altitude (as demonstrated by the Tibet ASγ array), a joint U.S. Mexcian collaboration has proposed to construct a water Cherenkov EAS array at high altitude. The detector known as the HAWC (High Altitude Water Cherenkov) Observatory would be constructed at the volcan Sierra Negra (Tliltepetl) in Mexico. With an altitude of 4100 meters above sea level (compared to 2600 meters above sea level for Milagro) and a dense sampling detector that encloses 22,000 square meters, HAWC is expected to have 15 times the sensitivity of Milagro and an energy threshold below 1 TeV. Figure 7 shows a computer-generated image of HAWC on the site in Mex-

Fig. 7. Artists view of the HAWC array at the volcan Sierra Negra (Tliltepetl).

ico. Unlike Milagro, HAWC would be composed of 900 individual water tanks. Each tank would be 5 meters in diameter and 4.6 meters tall, much larger than those used by Milagro or the Auger detector, and would have a PMT at the bottom of each tank looking up into the water volume. HAWC will have unprecedented sensitivity to the highest energy particle accelerators in our Galaxy, the sensitivity required to detect short flares from active galaxies, and the ability to make a detailed map of the diffuse gamma-ray emission in our Galaxy. For further details on HAWC see.[24]

5. Conclusions

Milagro has made several ground-breaking measurements that are important to expanding our understanding of the cosmic radiation that pervades our Galaxy. The first measurement of the Galactic diffuse emission near 10 TeV has shown that the so-called "GeV excess" may well be due to a larger than expected inverse Compton component. However, within the Cygnus Region there exists a TeV excess even with this enhanced inverse Compton component. This excess maybe due to the presence of a cosmic-ray accelerator within the Cygnus Region, or to as yet unresolved point sources that lie within this region. Milagro has also measured both large scale and intermediate scale anisotropies in the arrival directions of the local cosmic rays. While our measurement of the large-scale anisotropy agrees well with the previous results from the Tibet array, we have discovered a time dependence to the amplitude of the anisotropy. Since the amplitude seems to increase as the Sun goes from solar maximum to solar minimum, it is natural to conclude that the time dependence is due to solar modulation affects. Though it is critical to continue to follow this time dependence through the entire solar cycle. Finally, we have discovered two regions of localized excess in the cosmic ray arrival directions. These excesses are about an order of magnitude smaller than the large-scale anisotropy and the one near the helio-tail has an energy spectrum that is significantly harder than the cosmic-ray spectrum. The explanation

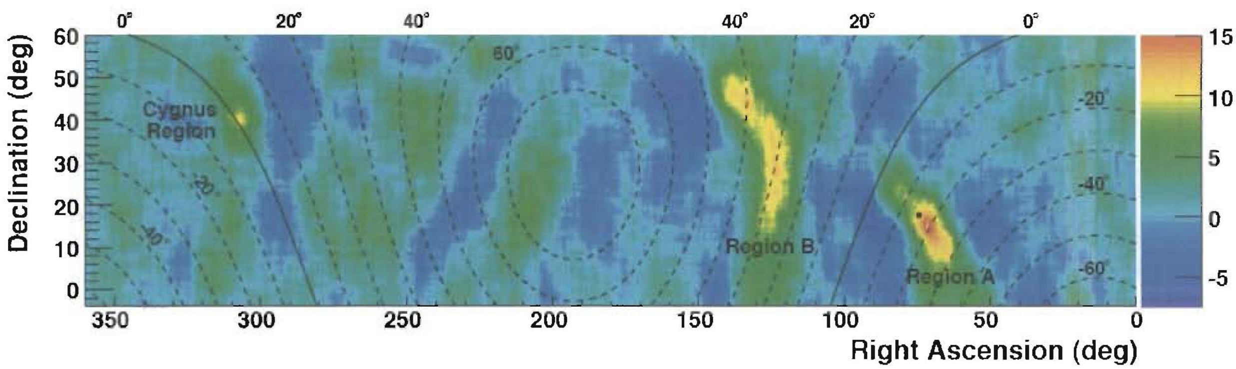

Fig. 5. The anisotropy in the local cosmic ray flux over intermediate scales (~10 degree smoothing length). The color scale shows the statistical significance of the excess in each 10×10 degree bin centered at the given right ascension and declination. The excess is measured with respect to a local average cosmic-ray flux within about 15 degrees of the location. The fractional excess in Region A is roughly 6×10^{-4} and in Region B roughly 4×10^{-4}.

of these excesses eludes explanation, though any explanation must include non-standard cosmic-ray diffusion and the presence of a cosmic-ray source quite close to the earth. The HAWC Observatory holds the promise to greatly expand our knowledge of the high-energy universe, in particular its ability to map the Galactic diffuse emission with relatively high resolution and to measure the highest energy gamma rays from Galactic sources will help us unravel the mystery of the cosmic radiation.

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