

Discovery of an Anomalous Cosmic Ray Component

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Abstract. Milagro is a water Cherenkov detector sensitive to gamma rays and hadronic cosmic rays with energies above a few hundred GeV. We have examined our data for the presence of intermediate scale ($\sim 10^\circ$) anisotropies in the arrival directions of the local cosmic rays. This analysis has revealed two regions with significant excess (greater than 12 standard deviations). The fractional excesses in the two regions are 6×10^{-4} and 4×10^{-4} , roughly one order of magnitude smaller than the large scale anisotropy previously reported by the Tibet AS γ and Milagro. We are able to rule out a gamma-ray origin to these excesses with high confidence. The effect is maximal for proton energies near 10 TeV. Because the Larmor radius of a 10 TeV proton in a $2\mu\text{G}$ magnetic field is 0.005 pc explanations of these observations are difficult, however they seem to imply a relatively nearby source and non-standard diffusion of cosmic rays in the solar neighborhood.

Keywords: Cosmic Rays, Anisotropy, Cosmic-Ray Source

I. INTRODUCTION

The study of the anisotropies in the local cosmic-ray arrival directions may hold clues to both the origins of the cosmic rays and their propagation through the Galaxy. Until recently these studies have been limited by the event statistics of the instruments to one-dimensional measurements (see [1] for a review). More recently, the Super-Kamiokande collaboration [2], Tibet AS γ collaboration [3], and the Milagro collaboration [4] have published so-called two-dimensional maps of the large-scale cosmic-ray anisotropy in the 1-100 TeV energy range. (In actuality these measurements do not compare the cosmic-ray rates at different declinations and are therefore a series of one-dimensional strip charts, comparing the relative cosmic-ray rate as a function of right ascension for different declinations.) In this paper we report on the observation of intermediate scale anisotropies in the local cosmic-ray arrival directions, those with angular scale of ~ 10 degrees [5].

Milagro is a water Cherenkov detector sensitive to gamma rays and cosmic rays with energies between a few hundred GeV and 100 TeV, with a median energy of detected cosmic rays of roughly 1 TeV. Milagro consists of a light-tight water reservoir measuring $80\text{m} \times 60\text{m} \times 6\text{m}$ deep. There are two layers of photomultiplier tubes (PMTs): a top layer of 450 PMTs under 1.2 meters of water and a bottom layer of 173 PMTs under 6m of water. The top layer of PMTs was used to reconstruct the

direction of the primary cosmic/gamma ray, the bottom layer was used to detect the penetrating component of hadronic air showers and thereby discriminate between gamma-ray and cosmic-ray initiated air showers. In addition to the main water reservoir, which was in operation beginning in July 2000, there is a 175 station “outrigger” array enclosing $\sim 40,000 \text{ m}^2$, which was incorporated into the detector in 2004. The outrigger array was used to locate the core of distant showers that triggered the water reservoir and thereby increase the effective area of Milagro to high-energy cosmic rays and gamma rays.

The outrigger tanks measured 1m deep by 3m diameter. They were lined with reflective Tyvek on the sides, bottom and top. A single PMT mounted at the top of each tank viewed the water volume. The trigger rate of Milagro was 1700 Hz and Milagro operated with a duty cycle in excess of 90% until operations ceased in April 2007. The angular resolution of the array (defined as the σ of a 2-dimensional Gaussian) varied from 1° to 0.5° depending upon the size of the event, with an average value of 0.75° .

II. ANALYSIS AND RESULTS

The search for intermediate scale cosmic-ray anisotropy is performed in a similar fashion as the standard gamma-ray analysis of Milagro (see [6]). The only differences are: no background rejection is applied to the data (resulting in roughly an order of magnitude more events in the analyzed data set) and the angular bin size used is 10° , larger than the standard bin size used for a search for point sources of gamma rays. As in reference [6] a “signal” map is constructed by summing the events as a function of right ascension and declination (originally in $01. \times 0.1$ degree bins, then summing these to form 10×10 degree bins) and the background is found by mapping the events for each 2-hour interval in local coordinates and integrating this “detector acceptance map” over the livetime of the detector (determined by the actual event times during the same 2-hour interval). The total number of events used in the analysis (after all cuts are applied) is 2.2×10^{11} and the median energy of these events is 1 TeV. The results are shown in Figure 1.

Three features are evident in Figure 1.

- An excess from the Cygnus Region of high statistical significance
- An excess from “Region A” at R.A. 70° declination 15°
- An excess from “Region B” centered at R.A. 130° , declination 30°

The excess from the Cygnus Region is consistent with gamma-ray emission at the flux level previously reported by Milagro [7]. The excesses from Regions A and B are not consistent with gamma-ray emission, as we will demonstrate below. The fractional excess from Region A is 6×10^{-4} and from Region B 4×10^{-4} .

III. HADRONIC NATURE OF THE OBSERVED EXCESSES

To investigate the nature (gamma ray or hadronic) of the observed excesses we utilize the ability of Milagro to discriminate between electromagnetic air showers and those containing muons (the result of hadronic interactions). Reference [6] describes the compactness parameter - the ratio of the number of PMTs in the bottom layer that are struck and the maximum number of photoelectrons (PEs) detected by a PMT in the bottom layer. In practice the distribution of compactness for gamma-ray events depends upon the spectrum of the gamma-ray source. A soft-spectrum gamma-ray source will tend to have a proton-like distribution in compactness space. Therefore, determining the nature of the primary particles causing each excess requires a method to independently determine the energy of the events (at least as an ensemble). To do this we use the fraction of outrigger tanks (f_{out}) that are struck in each event. Figure 2 shows the average event energy as a function of the natural logarithm of the fraction of outriggers struck for proton events.

Given the fact that both the energy estimator and the background rejection parameter can only be used in a statistical sense over an ensemble of events we proceed by assuming an energy spectrum for the observed excess of the form

$$dN/dE \propto E^\gamma \exp^{(E/E_c)}. \quad (1)$$

We then perform a simultaneous fit to the excess distribution in compactness space and in the f_{out} space for a gamma-ray source hypothesis and for a proton source hypothesis. In Region A the gamma-ray hypothesis leads to a minimum chi-squared in this 2-dimensional parameter space of 124 with 16 degrees of freedom. In contrast the proton hypothesis leads to a minimum chi-squared of 10.3 with the same number of degrees of freedom. Therefore, in Region A the gamma-ray hypothesis has a probability of about 10^{-18} of leading to the observed distribution in the 2-dimensional space, while the proton hypothesis is consistent with the data. For Region B the gamma-ray hypothesis has a minimum chi-squared of 84.8 while the proton hypothesis has a minimum chi-squared of 19.0 (again for 16 degrees of freedom). In Region B the gamma-ray hypothesis has a probability of 2×10^{-11} of leading to the observed distribution, while the proton hypothesis is consistent with the data. Note that these tests only apply to pure proton or pure gamma ray hypotheses, we have not considered possible admixtures of gamma rays and protons, nor set limits on the fraction of gamma rays that may be present in the excess.

The essence of the above arguments is straightforward. The observed compactness distribution of the excess would require a very soft gamma-ray spectrum source to be consistent with a gamma-ray hypothesis. However, examination of the f_{out} distribution is inconsistent with such a soft spectrum. This is explained further below.

IV. ENERGY DEPENDENCE OF THE OBSERVED EXCESSES

Having established the hadronic nature of the particles responsible for the observed excess, we now examine the energy dependence of the excess. In Figure 3 we show the fractional excess as a function of the natural logarithm of f_{out} for Regions A and B. Note, that if the excess had a spectrum identical to the cosmic-ray spectrum then the fractional excess would be constant (at some value) as a function of f_{out} . In Figure 4 we show the 1σ , 2σ , and 3σ allowed regions for the spectral index γ and cutoff energy E_c from Equation 1. Note that for Region A the 3σ contour does not extend to a value of the spectral index γ that is consistent with the cosmic-ray spectrum. In fact, for Region A this is clearly not the case - the chi-squared of the data compared to the mean value of the fractional excess has a chance probability of 2×10^{-6} . In Region B the same test yields a chance probability of 6×10^{-3} . (And indeed, Figure 4 shows that the 3σ contour extends to values of γ consistent with the cosmic-ray spectrum, while the contour extends to essentially infinite values of the cutoff energy.) Therefore, we can strongly rule out a cosmic-ray spectrum for the excess in Region A, though not for Region B. Additionally, in Region A we have strong evidence for an energy above which the excess vanishes, i.e. the 3σ contour does not extend to infinite energy in Figure 4. Note that systematic errors have not been accounted for in Figure 4. We estimate a $\sim 30\%$ systematic error in the absolute energy scale of the detector [6] and a systematic error of ± 0.2 in the spectral index due to variations in the trigger threshold due to atmospheric conditions, changing overburden (due to water on top of the cover of the reservoir), and an ice layer below the cover that alters the reflective properties of the water cover interface.

V. DISCUSSION

While non-uniform cosmic-ray source distributions and cosmic-ray transport affects could lead to the observed large-scale anisotropies, the explanation of the intermediate scale anisotropies discussed here presents a challenge. The gyroradius of a 10 TeV proton in a $2\mu\text{Gauss}$ magnetic field is 0.005 pc and the decay length of a 10 TeV neutron is 0.1 pc. Therefore, the most natural origin of this excess is within the heliosphere. Using the Hillas criteria $E_{max} = BV L$ (where B is the magnetic field strength, V is the characteristic velocity, and L is the characteristic length of the local acceleration site) Drury and Aharonian [9] find a maximum rigidity of 20 GV for reasonable values of the parameters, nearly

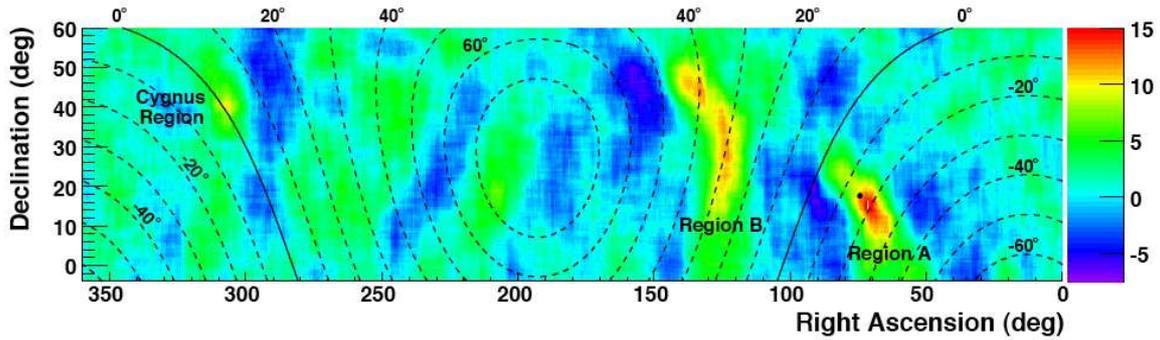


Fig. 1. The anisotropy in the local cosmic ray flux over intermediate scales (~ 10 degree smoothing length). The color scale shows the statistical significance of the excess in each 10×10 degree bin centered at the given right ascension and declination. The excess is measured with respect to a local 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} . Note for black and white version: the positive and negative fluctuations have the same grayscale at their extremes. Only the area of the map marked as Region A is a positive significance at this level. The other regions with similar grayscale are negative fluctuations.

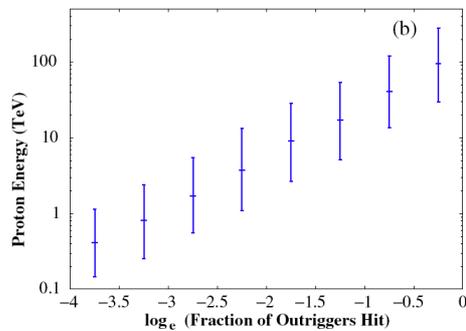


Fig. 2. The average energy of proton events as a function of the natural logarithm of the fraction of outrigger tanks struck. The error bars contain 68% of the events in each range.

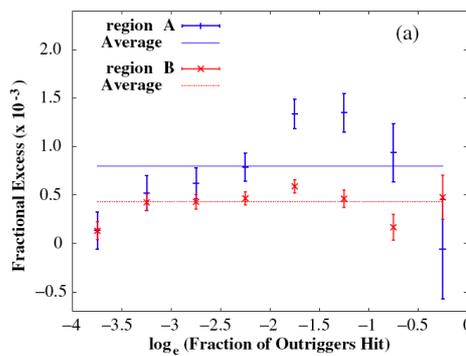


Fig. 3. The observed distribution in the natural logarithm of f_{out} of the excesses in Regions A and B. Compare with Figure 2 to see that the fractional excess (in both regions) is maximal at roughly 10 TeV.

3 orders of magnitude below the observed energy of the excesses. Salvati and Sacco [8] reach a similar conclusion based on the available energy budget at the accretion wake, which they estimate is about a factor of 50 too small to explain the observed excess flux (1×10^{-9} ergs $\text{cm}^{-2} \text{sec}^{-1}$) of cosmic rays from Region A.

Drury and Aharonian [9] also discuss a possible neutron source near the heliotail, caused by the accretion

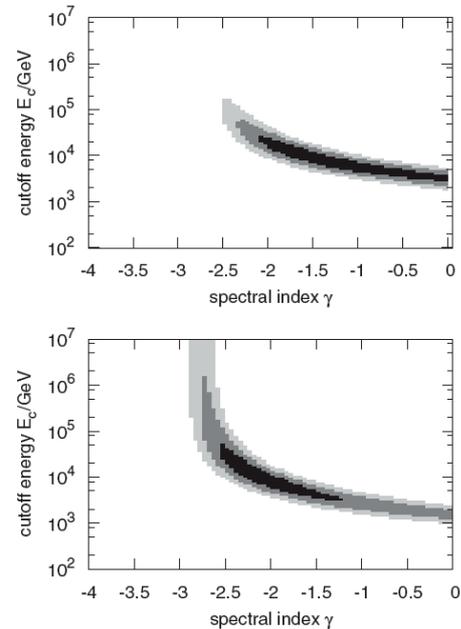


Fig. 4. The allowed regions of parameter space (1σ , 2σ , and 3σ contours shown) of spectral index γ and energy cutoff E_c from Equation 1. This analysis was performed assuming a purely proton nature to the observe excess. The top figure shows the results for Region A and the bottom for Region B. Note that in the bottom figure the 3σ contour extends to essentially infinite energy in the energy cutoff parameter for a spectral index consistent with that of the cosmic rays. This indicates that we can not rule out a cosmic-ray spectrum for the excess in Region B at the 3σ level. This is contrast to Region A, where the 3σ contour does not extend to a spectral index consistent with the cosmic-ray spectrum and a cutoff is clearly observed.

wake of the Sun as it travels through the interstellar medium. This wake would build-up a target mass for incoming cosmic ray interactions, leading to neutron production. However, they demonstrate that this affect would lead to flux roughly 6 orders of magnitude smaller than that observed here. Thus, despite the coincident location of Region A with the heliotail of the solar system, it appears that one must look beyond our local heliosphere to understand the origin of this excess.

Absent a local origin, one must invoke non-standard diffusion of cosmic rays to explain the small angular extent of the observed excess. As Drury and Aharonian point out, even particles traveling along well organized magnetic field lines will arrive with a large distribution of pitch angles and therefore appear to arrive from $2\pi sr$ of the sky. Their solution to this dilemma is to postulate a magnetic trap like configuration of the field between the source and the Earth, where the field converges between the Earth and the source and diverges again (with a compression ratio of about 1:20) before reaching Earth. See Figure 1 of [9] for details. They limit the source distance to roughly 100 pc.

Salvati and Sacco [8] point out that such freely flowing particles (non-diffusive propagation) would imply a very short travel time from the source to the Earth, less than 1000 years, and it is difficult to understand how such a local supernova would have escaped observation. Alternatively, they suggest a modification to the proposal of Drury and Aharonian, where the particles diffuse for at least a portion of their journey from the source to the Earth, in particular from the source to the convergent section of the magnetic field lines, followed by free streaming to the Earth. The most likely candidate for the source, according to [8] is the Geminga supernova. The energy budget is consistent with 1% of a typical supernova explosion (1.5×10^{49} ergs) and the distance to the original location of the supernova could be consistent with the 100 pc limit, if the radial velocity of Geminga is of order 160 km sec^{-1} .

VI. CONCLUSIONS

Milagro has observed an anomalous component to the local cosmic rays. This anomaly manifests itself as two

regions of intermediate scale anisotropies (with fractional excesses near 5×10^{-4} of the cosmic-ray intensity). One of the regions (Region A above) has an energy spectrum that is inconsistent with the local cosmic-ray energy spectrum. Instead it is characterized by a hard spectral index at low energies (between 1 and 10 TeV) and a cutoff above 10 TeV. Such features in the local cosmic rays are difficult to understand in the absence of a local source (<100 pc) and non-standard propagation of cosmic rays between the source and the Earth. Drury and Aharonian [9] have proposed a geometry of the magnetic field lines connecting the source and the Earth where the fields converge and then diverge, with a compression factor of roughly 20 (a geometry similar to that of a magnetic trap). Using such a magnetic field configuration Salvati and Sacco [8] suggest that the original supernova event that led to the Geminga pulsar may be the source of this anomaly. While it is too early to determine with confidence the true explanation of these observations, they are pushing our understanding of cosmic-ray propagation and could lead to a better understanding of the history of our local interstellar environment.

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