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A Harmonic Analysis of the Large Scale Cosmic Ray Anisotropy

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Abstract: Here we present the results of a harmonic analysis of the large scale cosmic-ray anisotropy as observed by the Milagro observatory. The Milagro observatory is a water Cherenkov detector located in the Jemez mountains outside of Los Alamos, New Mexico. With a high duty cycle and large field-of-view, Milagro is an excellent instrument for measuring this anisotropy with high sensitivity at TeV energies. We show a two-dimensional map of the sidereal anisotropy generated by the fitting of three harmonics to separate declination bands taken from a six year data sample consisting of 150 billion events, the largest such data set in existence. We observe an anisotropy with a magnitude around 0.1% for cosmic rays with a median energy of 3 TeV. The dominant feature is a deficit region in the direction of the Galactic North Pole with a range in declination of -10 to 45 degrees and 150 to 225 degrees in right ascension. We also present results from an examination of the time evolution and the energy dependence of the anisotropy signal.

Introduction

Observation of the sidereal large scale cosmic-ray (CR) anisotropy at TeV energies is a useful way of probing the magnetic field structure in our interstellar neighborhood. In addition to this, Compton and Getting introduced a theory[1] of sidereal CR anisotropy which predicts a dipole effect due to the motion of the solar system around the galactic center with an increase on the order of $\sim 0.1\%$ in the direction of motion.

In this paper, we present the results of a harmonic analysis of the sidereal sky anisotropy as observed by the Milagro observatory.

Milagro Observatory

The Milagro observatory is a water Cherenkov detector designed to monitor extensive air showers produced by gamma-rays and hadrons hitting the Earth's atmosphere. Milagro is located in New Mexico at a latitude of 36°, with an altitude of 2630 m above sea level, possessing a large field of view of ~2sr and a high duty factor of $> 90\%$. The detector is composed of a 80m×60m×8m pond surrounded by a 200m×200m array of 175 "outrigger" tanks. The central pond has two layers. The top "air shower" layer has 450 PMTs under 1.4m of water. The bottom "muon" layer has 273 PMTs 6m under the surface.

The data used in this analysis has been collected by Milagro from July 2000 through July 2006. During this time there has been an average trigger rate of ~1700 events per second of which the majority are due to cosmic-ray showers. After event reconstruction we require accepted events to have triggered at least 90 PMTs in the top layer and have a zenith arrival angle of $\leq 50^\circ$. After these cuts we have a data set consisting of 1.52×10^{11} cosmic-ray events with a median energy of 3 TeV.

Data Analysis

The cosmic-ray events are recorded according to their arrival direction from -10° to 80° in declination and -50° to $+50^\circ$ in hour angle. The events are collected over a 30 "minute" period, where "minute" is defined in the three following time frames: sidereal (366.25 days/year), universal (365.25 days/year) and anti-sidereal (364.25 days/year). These events are placed into histograms with $5^\circ \times 5^\circ$ bins. Each of the 48 half hour histograms for the time frame of interest is then analyzed by using the method of forward-backward asymmetry (FB). This method is employed to remove the effects of varying trigger rates due to changing atmospheric and detector conditions between these 30 minute periods. Since Milagro scans the sky with the motion of the Earth, we have no information about modulation in the declination direction. For this reason each 5° dec. band is treated as a seperate observation and is analyzed independently. We make the assumption that the large scale anisotropy in any given dec. band can be modelled by a fourier series and that it is a small modulation of a nearly isotropic signal. Three harmonics (the fundamental and next two longest) have been found to be optimal for this method. This allows us to see large scale effects having a width in r. a. of greater than $\sim 40^{\circ 1}$.

Using this model, the equation for the (normalized) rate is:

$$R(\theta) = 1 + \sum_{n=1}^{3} \gamma_n \cos n(\theta - \phi_n) \qquad (1)$$

$$\gamma_n \ll 1$$

To determine the fourier coefficients we first calculate the FB asymmetry for each half hour histogram as a function of α (see Figure 1).

$$FB(\theta, \alpha) = \frac{R(\theta+\alpha) - R(\theta-\alpha)}{R(\theta+\alpha) + R(\theta-\alpha)} \qquad (2)$$

where θ = mean time in degrees of the half hour histogram and α ranges from 2.5° to 47.5° in 5° steps. These values of FB are binned in a 2-D histogram of α vs. θ which is then fit with the following function obtained by substituting (1) in (2), applying the appropriate trigonometric identities and using the fact that $\gamma_n \ll 1$.

$$FB(\theta, \alpha) \approx \sum_{n=1}^{3} -\gamma_n \sin(n\alpha) \sin(n(\theta - \phi_n)) \qquad (3)$$

The coefficients thus obtained are used to reconstruct the anisotropy as a fractional difference from isotropic in a given dec. band.

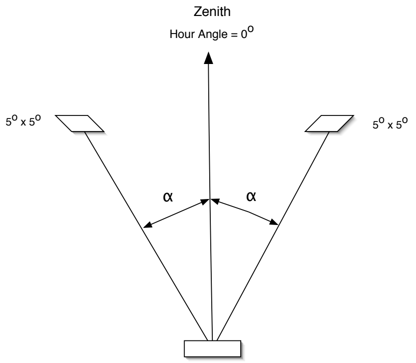

Figure 1: Diagram showing the definition of α used in the calculation of the forward-backward asymmetry for a single dec. band and a given 30 minute histogram. α is in the direction of hour angle.

To estimate the systematic errors for the sidereal signal we examine the anti-sidereal maps. Monte carlo simulations show that large, time dependent variations in universal time will affect both the sidereal as well as the anti-sidereal signals with equal amplitude but arbitrary phase. Since there are no physical processes which occur in the anti-sidereal time frame the signal should be zero when data sets of an integral number of years are used. Given this we can estimate the systematic error for the sidereal analysis due to universal time fluctuations by calculating variations in the anti-sidereal signal.

Results

Fig. 2 shows the results of this analysis for the sidereal sky. The ”tail-in” and ”loss-cone” regions observed by previous studies [3][4] are consistent with what is seen here. The central-deficit region extending from 150° to 225° in r.a. and -10° to 45° in dec. is the dominant feature in this map which we choose to focus on to determine the time variation and energy dependence due to its large area and stability in position over time. We find the average value of the deficit in the region de-

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[1] For an analysis sensitive to features with an extent smaller than $\sim 30^\circ$ in r. a. see[2].

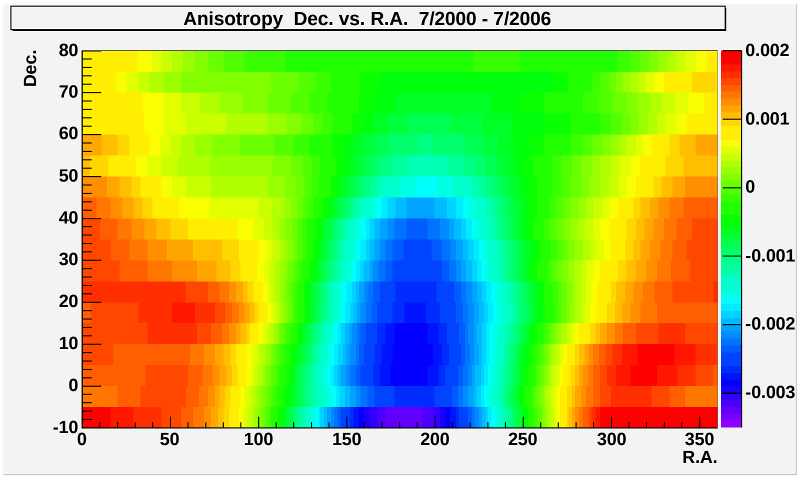

Figure 2: Fractional difference of the cosmic ray rates from isotropic in equatorial coordinates as viewed by Milagro for the years 2000-2006. The color bin width is 1.0×10^{-4} reflecting the average measurement error. The median energy is 3 TeV.

fined by $5^\circ \leq$ dec. $\leq 35^\circ$ and $160^\circ \leq$ r.a. $\leq 210^\circ$ to be (-2.5 $\pm$ 0.049 stat. $\pm$ 0.19 syst.)$\times 10^{-3}$ giving a 10.5σ signal after the systematic and statistical errors are added linearly.

With the large number of events collected, we can split the data into yearly sets and repeat the averaging procedure to find variation of the signal in the central-deficit region over time. As can be seen in Fig. 3 there is evidence of a strengthening of the signal in this region over this six year period by a factor of ~ 2. However, even though the chi square for the linear two-parameter fit is much better than that for the flat one-parameter fit, the latter still has a probability of $\sim 1\%$. This coupled with the lack of a specific model for the time variation prevents a conclusive statement about the increase in magnitude. Extending this analysis to include more years of data should help to clarify this observation.

To determine the energy dependence of the signal we employed the energy estimation procedure outlined in [5]. The mean depth of the central-deficit region is calculated as before and listed in Table 1 for a number of median energies. There is evidence that the signal is constant up to about 20 TeV. There is some indication that the signal weakens at the highest energy bin with median energy of ~ 80 TeV, but the deviation from constant is only at the 2σ level.

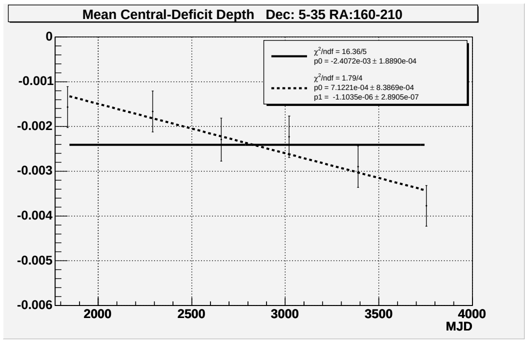

Figure 3: Mean depth of the central-deficit region vs. MJD for yearly sets from 2000-2006. The error bars are the stat. + sys. errors. The mean is taken from 5° to 35° in dec. and 160° to 210° in r.a. The solid line is the flat one-parameter fit and the dashed is the linear two-parameter fit. The χ^2/ndf for the fits are 16.4/5 and 1.8/4 respectively.

Energy (TeV)	Mean Central-Deficit Depth $\times 10^{-3}$
1	-2.54 ± 0.07
20	-2.63 ± 0.13
80	-1.56 ± 0.44

Table 1: Mean depth of the central-deficit region for three median energies. The resolution for the energy estimation procedure used here is $\sim 50\%$ for energies around 1 TeV and improves to $\sim 35\%$ for energies 10-20 TeV and above.

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