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The Cosmic Ray Moon Shadow Seen by Milagro

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Abstract. The Milagro cosmic ray detector, a large-area EAS water Cherenkov experiment, easily detects the blockage of TeV cosmic rays by the moon. The absence of these cosmic rays can be used to calibrate the absolute energy scale and the directional event reconstruction of Milagro using the Earth's magnetic field as a known quantity. These data can also put limits on the antiparticle flux of TeV cosmic rays.

1 Introduction

Milagro is a large-area EAS water Cherenkov ground array located at Los Alamos National Laboratory at an atmospheric depth of 750 g/cm^2. There are two layers of photomultiplier tubes (PMTs), one under 1.5 meters of water and another below it under 6 meters of water. As in other EAS array experiments, the arrival time and direction of an air shower is reconstructed using pulse times from the PMTs. For more information about the experiment see Sullivan (2001).

The Milagro experiment easily detects the blockage of cosmic rays by the moon. Figures 2 and 3 demonstrate this effect. As observed from the Earth the moon is approximately 0.52° degrees in diameter. Over the year and a half of operation Milagro has obtained 3776 hours of observation time on the moon when it was 15° or more above the horizon. In this time 7.03×10^4 events per square degree along the path traveled by the Moon triggered 45 or more PMTs in Milagro. Thus one expects the blockage of approximately 5.97×10^4 cosmic rays. Of these events, Milagro measures 5.5×10^4 missing events within 6° of the moon (figure 1). Of course these numbers depend on the criteria used to select events.

2 Map Creation and Background Estimation

To create a map in the region of a source in the celestial sky, the directions of reconstructed events are mapped according to some local two dimensional spherical coordinate system such as the equatorial coordinate system that uses hour angle and declination axes. A second map, which is rotated by the current hour angle of the celestial source with with respect to the first map, is also created. As the hour angle of the source is continuously changing, this rotation rotation is also changing. This second map is the source map, having its position constant with respect to the celestial source. If the first mapping is in equatorial coordinates then the second mapping is in celestial coordinates with axes of right ascension and declination. For our purposes the maps were approximated as two dimensional histograms with the bins are $0.1^\circ \times 0.1^\circ$, necessitating a change in the rotation angle between the two maps every 24 sidereal seconds.

To estimate the background in the source map, we divide the local coordinate map (the first map) by the number of events used to construct that map, giving a normalized probability distribution covering every point of interest on the local sky. This distribution is then convolved with the event rate as a function of the source's hour angle (or equivalently, sidereal time) to give give the expected background. This method is effectively similar to methods outlined in section 2.5 of Alexandreas, *et al.* (2001). For display purposes, both the source map and the background map are smoothed by a uniform distribution of a size on the order of the point spread function.

Figure 2 shows a plot of the event excess in the vicinity of the moon using the above method exactly as outlined. Mapping the moon in this way has two drawbacks. First, in this plot all cosmic rays are not deflected in the same direction with respect to the moon due to the moon's motion through the sky. This effect elongates the moon in the vertical direction. Second, the method outlined above includes the area around the moon in the estimation of the expected background of the moon. This is wrong. After a year and a half of operating Milagro the moon has blocked enough events that it is necessary to remove events in the region of the moon to correctly estimate the expected background. Including events from the region of the moon leads to an over estimate of the background along the strip of the moon's mo-

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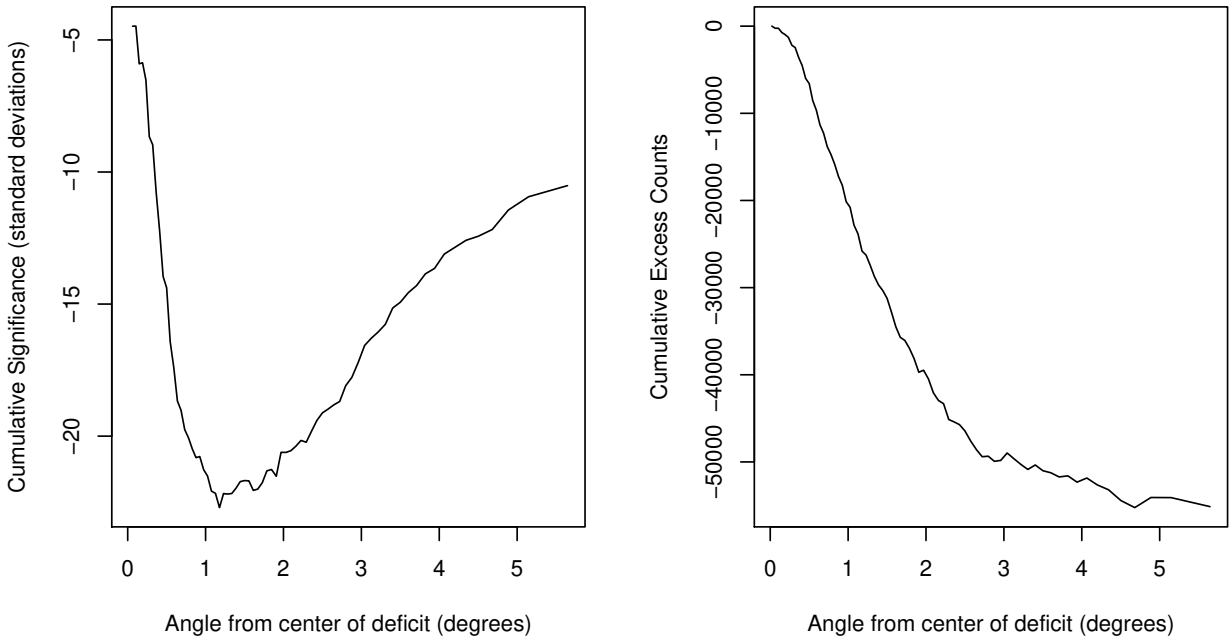

Fig. 1. Plots of cumulative excesses as a function of angle from the center of the deficit. The plot on the left is in units of standard deviations. The plot on the right is actual number of EAS events.

tion through the sky and a nonstatistical background distribution.

Figure 3 shows a rotated mapping where the expected cosmic ray deflection is along the abscissa. The expected direction of cosmic ray bending was calculated from a simulation that traced cosmic rays through the Earth's magnetic field (Wascko , 2001). These values were then used to rotate the map every two hours. The analysis in figure 3 also removes the area around the moon from the calculation of its own background. A background is then calculated as before with a renormalization to the local event probability distribution. This correction is necessary for calculating a proper excesses as in figure 1. Both corrections lead to a moon shadow that is more elliptical, elongated in the direction of the magnetic deflections. The actual shape of the shadow with deflections at higher angles becomes apparent.

3 Energy Calibration

Absolute energy calibration of EAS detectors is difficult, and usually relies on computer simulations of air showers. However, the blockage of cosmic rays by the moon and their deflection in the Earth's magnetic field provides Milagro with a simulation-independent energy calibration. The apparent deflection the moon's cosmic ray shadow from the position of the moon depends only on the Earth's magnetic field and the rigidity of the primary cosmic rays that cause the extensive air showers detected by Milagro. If we take the Earth's magnetic field as a known quantity, and use the particle mass distribution around a TeV as measured by balloon experiments (**?**), we can use the observed shadow deflection to constrain the median energy of the cosmic rays whose showers trigger Milagro.

The mean deflection of particles can be measured accurately, due to the large deficit caused by the moon. However, the deflection angle is relatively small ($\approx 0.4^{\circ}$) compared to the point spread function of Milagro, as can be seen in the figures. The deflection is inversely proportional to the median energy of the cosmic rays that trigger Milagro, assuming a relatively constant average cosmic ray mass over a few TeV. Thus, small errors in the measured deflection lead to larger errors in median energy estimation. Given these limitations, we can set limits within a factor of 2 on the median energy of the cosmic rays that trigger Milagro. Better upper and lower limits will be presented at the International Cosmic Ray Conference.

4 Evaluating Event Reconstruction

Since the expected deviations due to the Earth's magnetic field lie along the abscissa in figure 3, the vertical spread of the deficit in that plot should be due only to the point spread function of Milagro convolved with the shape of the moon itself. This allows us to set firm upper limits on the statis-

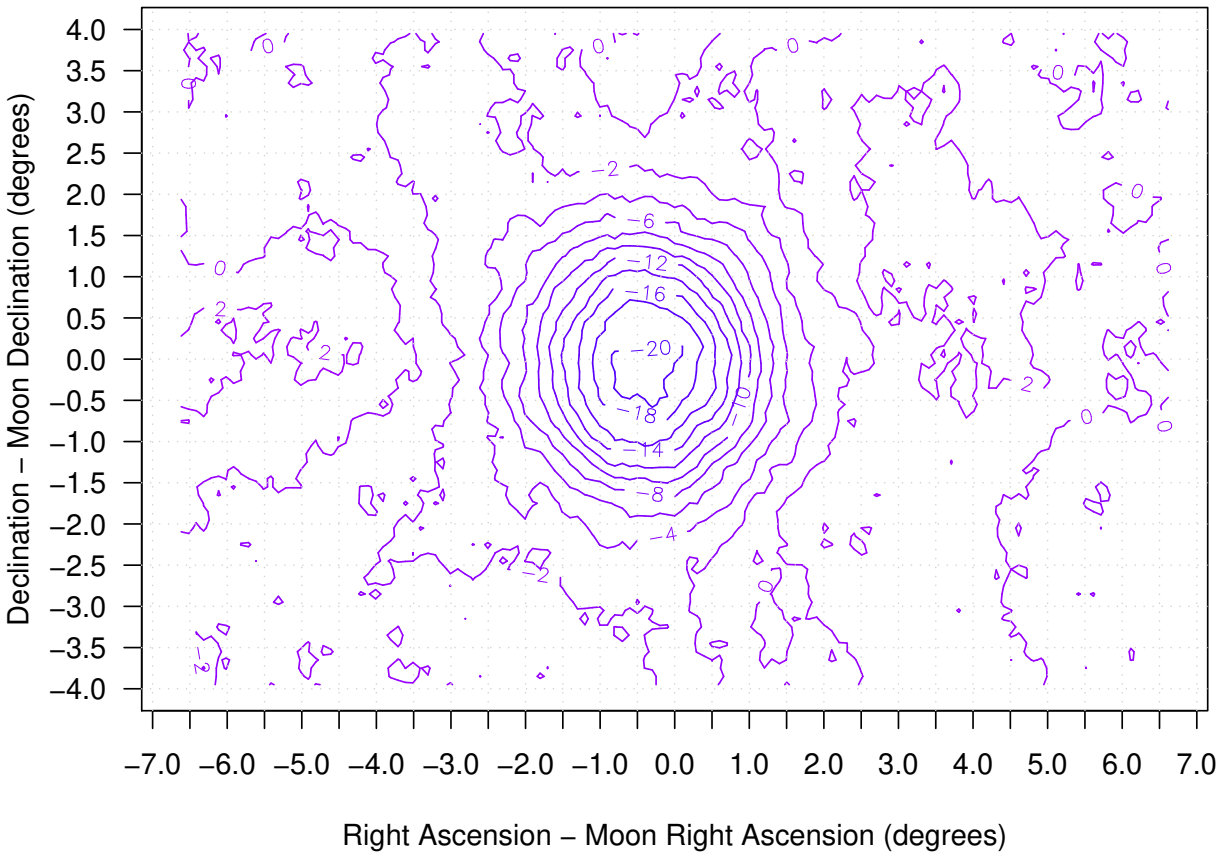

Fig. 2. Milagro event map of the region around the moon using right ascension and declination coordinates. Contours are labeled in units of standard deviations from a normal distribution. The estimated background used to make this map includes data from the region of the moon itself. This results in the small excesses seen to the left and right of the moon's position at 0 relative declination.

tical error of EAS directional reconstruction ("pointing") by the Milagro array. When we deconvolve the moon from vertical spread of the deficit in figure 3, we obtain a value of XX. The value obtained via this technique is an upper limit because the observed spread can only be worse than the statistical error of the pointing. We expect even better pointing on astrophysical sources of gamma rays, as simulations indicate that gamma-initiated airshowers are better reconstructed than hadronic air showers due to their greater particle uniformity at ground level. A more exact upper limit will be presented at the conference.

This upper limit is consistent with another measurement of our statistical pointing error, Δ_{eo}. Δ_{eo} is calculated by reconstructing every event twice, each time with half the PMTs in Milagro. The acutal statistical error in the pointing should then be around half the value of Δ_{eo}.

5 Antiparticle search

Just as we observe a shadow in the direction that we expect (to the left of the moon in figure /refgoodmoon), we can search for a complimentary shadow due to antiparticles to the right of the moon. This problem is complicated by Milagro's large point spread function that smears the particle shadow across the moon's location. Such a search yields limits at around the 10% level. More accurate limits will be presented at the conference.

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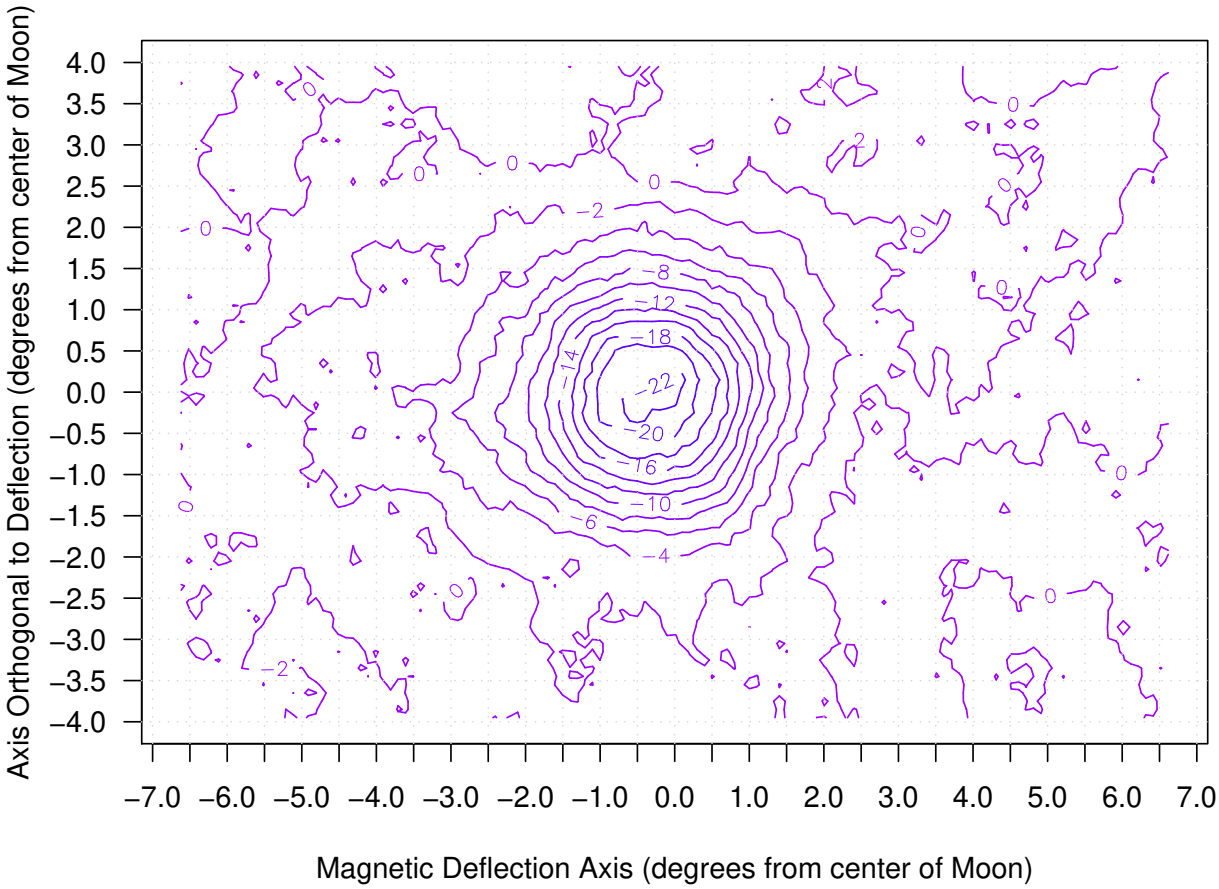

Fig. 3. Milagro event map of the region around the moon. Contours are labeled in units of standard deviations from a normal distribution. The expected cosmic ray deflections are to the left of the moon along the abscissa. The estimated background used to make this map excludes the region around the moon itself. Deflections at high angles to left are readily apparent.

References

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