Proceedings of ICRC 2001: 1 © Copernicus Gesellschaft 2001

ICRC 2001

The Cosmic Ray Moon Shadow Seen by Milagro

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Abstract. The Milagro cosmic ray detector, a large-area extensive air shower (EAS) water Cherenkov experiment, easily detects the blocking 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 magnetic spectrometer. These data can also be used to set 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 1.35 meters of water and another below it under 6 meters of water. For this study only data from the top layer of PMTs are used. As in other EAS array experiments, the direction of an air shower is reconstructed using pulse times from the PMTs. The experiment is sensitive to air showers with primaries from a few hundred GeV to 10's of TeV. 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 2.81×10^5 events per square degree along the path traveled by the Moon triggered 45 or more PMTs in Milagro. Thus one expects the blocking of approximately 5.97×10^4 cosmic rays. Of these events, Milagro measures $5.5 \times 10^4 \pm 5.08 \times 10^3$ missing events within $6°$ of the center of the moon's shadow (Figure 1). These numbers depend on the criteria used to select events.

Between the Earth and the Moon the paths of cosmic rays bend due to the Earth's magnetic field. At the typical energies detected by Milagro, this deflection is around $0.6°$c/TV. This deviation is useful in estimating Milagro's energy sensitivity and possibly differentiating particles from antiparticles, which bend in opposite directions in the Earth's magnetic field.

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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 respect to the first map, is also created. As the hour angle of the source is continuously changing, this 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 $0.1° \times 0.1°$ bins, 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 the expected background. This method is effectively similar to methods outlined in section 2.5 of Alexandreas (1993). For display purposes only, both the source and background map are smoothed by a uniform distribution of a size on the order of the point spread function ($\sim 1°$).

Figure 2 shows a plot of the event densities in the vicinity of the moon using the above method exactly as outlined.

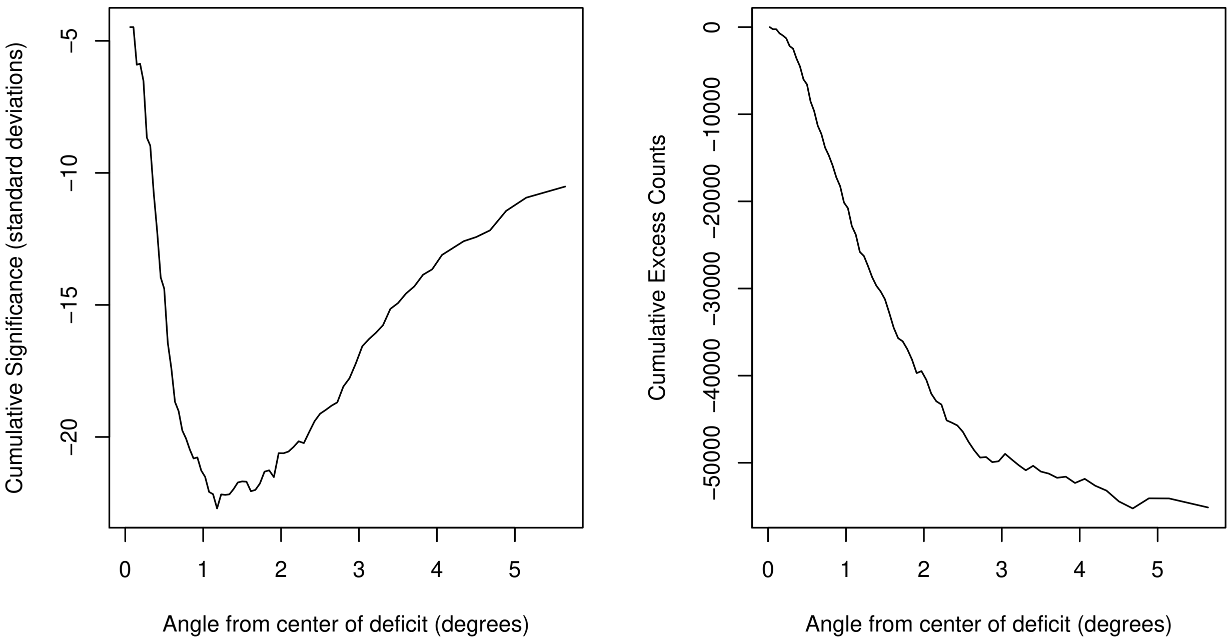

Fig. 1. Plots of cumulative excesses as a function of angle from the center of the deficit caused by the moon. The plot on the left is in units of standard deviations. The plot on the right is actual number of EAS events.

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 with respect to the local magnetic field. This effect elongates the moon in the figure's vertical direction. Second, the method outlined above includes the area around the moon in the estimation of the expected background of the moon. After a year and a half of operating Milagro the moon has blocked enough events that it is necessary to remove events in the moon's shadow when estimating the expected background. Including events from the region of the moon leads to an underestimate of the background along the strip of the moon's motion through the sky and a nonstatistical off-source 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 such that the direction of magnetic deflection appears horizontal and to the left. 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 the 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 large angles from the moon becomes apparent.

3 Energy Calibration

Absolute energy calibration of EAS detectors is difficult, and relies on computer simulations of air showers. However, the blocking 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 of 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 trigger Milagro. If we take the Earth's magnetic field as a known quantity, and use the particle mass distribution around 1 TeV as measured by balloon experiments (Wiebel-Sooth, 2001; Asakimori, 1998), 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 ($\approx 0.47°$) compared to the point spread function of Milagro, as can be seen in the figures, and it is inversely proportional to the median rigidity of the cosmic rays that trigger Milagro (Wascko, 2001). Thus, small errors in the measured deflection lead to large errors in median energy estimation. Given these limitations,

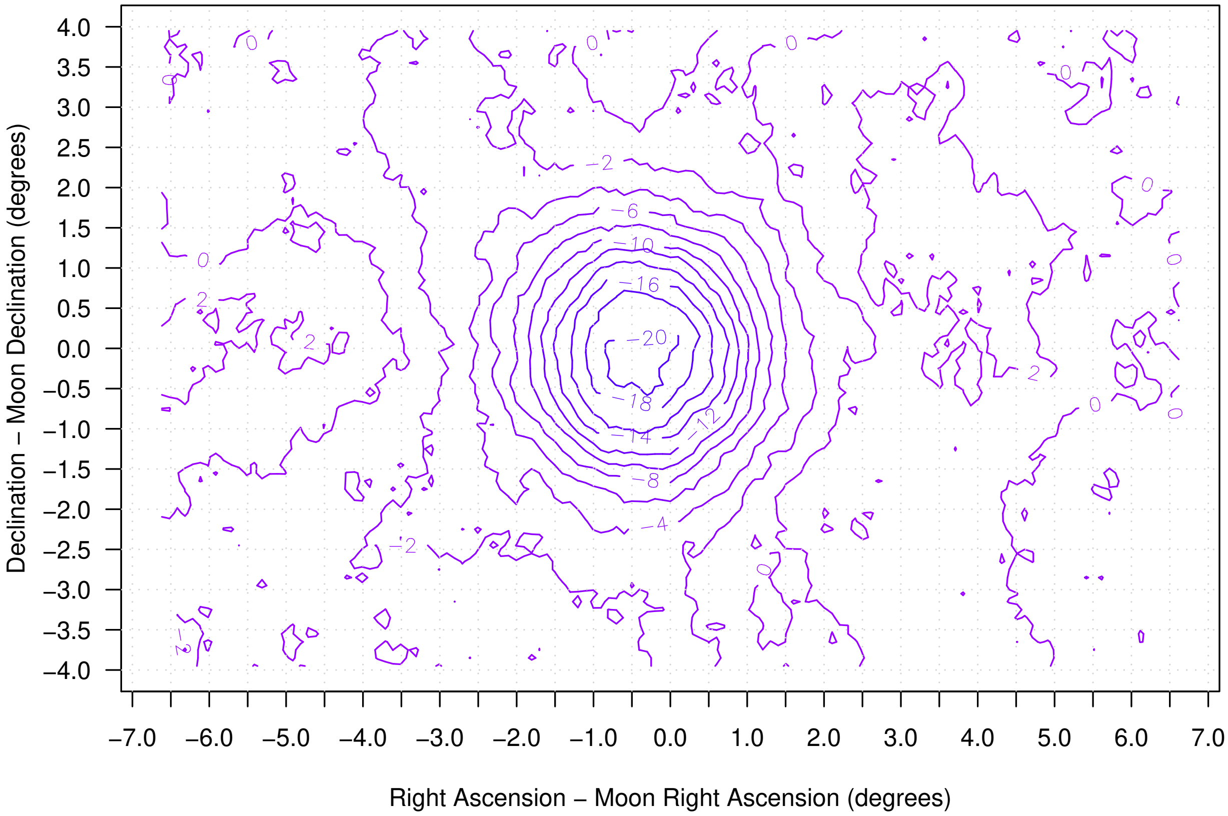

Fig. 2. Milagro event map of the region around the moon using right ascension and declination coordinates. Contours are labeled in units of standard deviations from a normal distribution. The estimated background used to make this map includes data from the region of the moon itself. This results in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

we can set limits within a factor of 2 on the median energy of the cosmic rays that trigger Milagro. Upper and lower limits will be presented at the 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 statistical error of EAS directional reconstruction ("pointing") by the Milagro array. When we deconvolve the moon from the deficit in Figure 3, we obtain vertical spread of $0.75°$ if we assume a two-dimensional Gaussian shape for the deficit.

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. This value is smaller than a naive glance at Figure 1 would indicate. The deficits in Figure 1 include the width of the $0.52°$ moon and the spread due to the Earth's magnetic field. We expect even better pointing on astrophysical sources of gamma rays, as simulations indicate that gamma ray initiated airshowers are better reconstructed than hadronic air showers due to their greater likelihood of triggering Milagro at small distances from the detector. The upper limit is consistent with another method of measuring Milagro's statistical pointing error, $\Delta_{EO}/2$. Δ_{EO} is the angular difference between two different reconstructions of the same shower with only half of the PMTs in Milagro (Atkins, 2000). A more exact upper limit on the statistical pointing error will be presented at the conference.

5 Antiparticle Search

Just as we observe a shadow offset in the direction that we expect (to the left of the moon in Figure 3), 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 around the

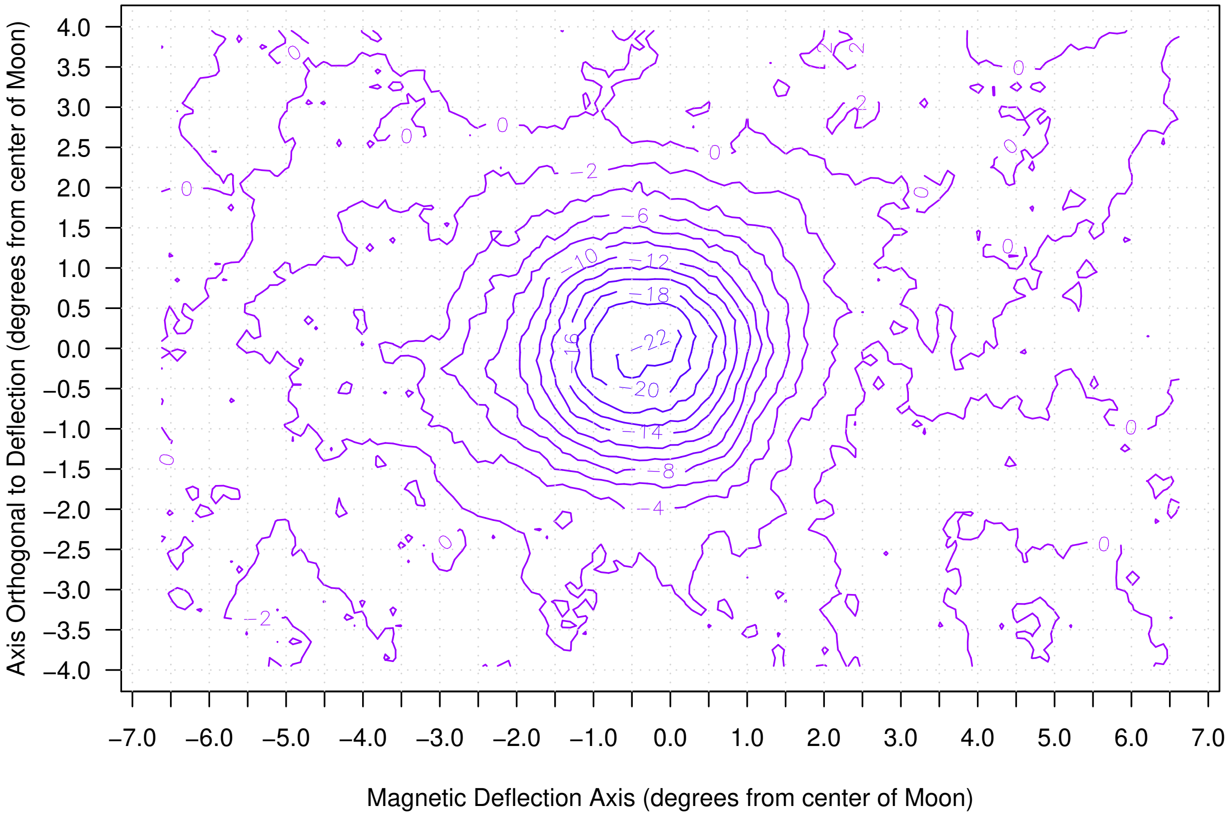

Fig. 3. Milagro event map of the region around the moon. Contours are labeled in units of standard deviations from a normal distribution. The expected cosmic ray deflections are to the left of the moon along the abscissa. The estimated background used to make this map excludes the region around the moon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

10% level of the cosmic ray particle flux. More accurate limits will be presented at the conference.

6 Conclusions

The moon is an interesting and useful object for low energy EAS array detectors. Limits on the errors of event reconstruction and limits on antiparticle fluxes can be set. Absolute energy calibration of arrays is also possible.

Acknowledgements. This work is supported by the Department of Energy Office of High Energy Physics, the National Science Foundation, the LDRD program at Los Alamos National Laboratory, Los Alamos National Laboratory, the University of California, the Institute of Geophysics and Planetary Physcis, the Research Coportation, and the California Space Institute. We would also like to recognize the hard work of Scott Delay and Michael Schnieder, without whom these data would not exist.

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