The Cosmic Ray Shadows of the Moon and the Sun Detected by the Milagro Gamma Ray Observatory

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Abstract

The Milagro gamma ray observatory has operated since June, 1999 which spans the solar activity maximum of the 23rd solar cycle (in 2000). An analysis of the data shows that the shadows of the sun and moon have each been detected with high significances by observing cosmic-ray deficits from these directions. In the current Milagro measurement the shadow of the sun is significantly weaker than that of the moon. As expected, the measured positions of the deficits differ from the nominal positions of these objects due to cosmic-ray bending in the magnetic fields of the earth and the sun. The different displacements of the shadows of the sun in the "away" and "toward" sectors of the interplanetary magnetic field(IMF) are consistent with no shift of the shadow given the statistical uncertainty in the measurement. The result of this analysis will be presented.

1. Introduction

It was originally proposed by Clark[1] that the shadow of the sun and moon could be observed with high-energy cosmic rays. Almost all the cosmic rays are charged and propagate through interplanetary space to arrive at earth. Therefore, these high-energy particles will be deflected by the solar magnetic field, the IMF, and the geomagnetic field. These magnetic field effects can be detected by an air shower array with good angular resolution and a sufficiently low energy threshold.

The observation of the shadow of the sun may give us some information on the solar magnetic field and the IMF. While the observation of the shadow of the moon can be used to: (1) estimate the angular resolution of the air shower array and its systematic pointing errors; (2) calibrate the energy response of the air shower array; (3) measure the antiproton-proton ratio at TeV energies. The Tibet AS_γ array has detected the shadow of the sun in the 10 TeV cosmic ray flux[2]. This observation shows that the cosmic rays in the "away" (positive) and "toward"(negative) field sectors in the interplanetary space are deflected in the opposite directions according to the IMF polarity. Further observations by the Tibet group show that the yearly movement of the shadow of the sun is correlated

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with a time variation of the large scale structure of the solar magnetic field and the IMF[3,4] which suggests a relation with the solar activity.

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2. Data analysis

The data used in this analysis were taken from June 1999 to Febuary 2003. The mean VME trigger rate with the trigger condition of 60 out of 450 PMTs hit in the top layer is about 1750 Hz. Every event satisfying the trigger condition is reconstructed online to determine its shower parameters. Approximately 90% of the triggered events are reconstructed successfully with an angular resolution of 0.75°. Events satisfying the following two conditions are chosen to analyze the shadows of the moon and the sun: (1) the number of fitted PMTs nFit≥50; (2) the zenith angle $\theta \leq 45°$. In total, about 1.68×10^8 and 1.81×10^8 events in the region of ±10.05° around the moon and the sun are selected, respectively.

The analysis of the shadows of the moon and the sun searches for a deficit of events relative to the cosmic ray background in the direction of the moon and sun. The region of ±10.05° around the moon or the sun is divided into 201×201 bins. For each event, the angular distance to the moon or the sun and the position angle relative to the north celestial pole are calculated to determine in which bin it falls. The signal map was obtained by this process. To obtain the background map, a direct integration method is used which is described in detail in[5,6]. The optimal bin size, related to the point spread function, has a radius of 1.2°. The signal map and background map are summed for each bin according to this optimal bin size.

3. Results

3.1. The shadow of the moon

Figure 1 shows the significance map of the deficit events around the moon. The maximum deficit position is at (-0.55°±0.04°,-0.28°±0.04°). The significance of the bin with the largest deficit is 33.5σ. Analysis shows that each month the significance of the deficit is about -4σ to -6σ depending on the data sample. This confirms the stability of the Milagro detector. The observed westward and southward shifts are consistent with that expected for the energy response of the

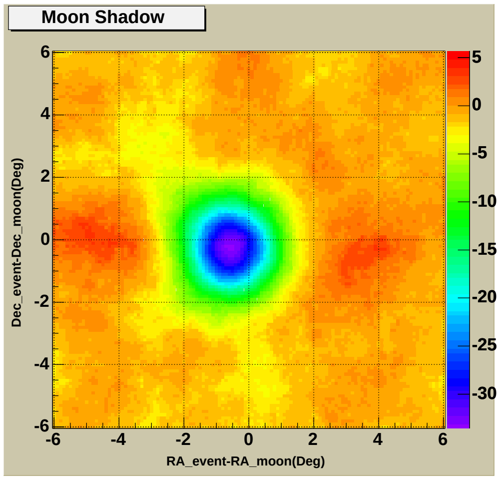

Fig. 1. The deficit significance map of the shadow of the moon

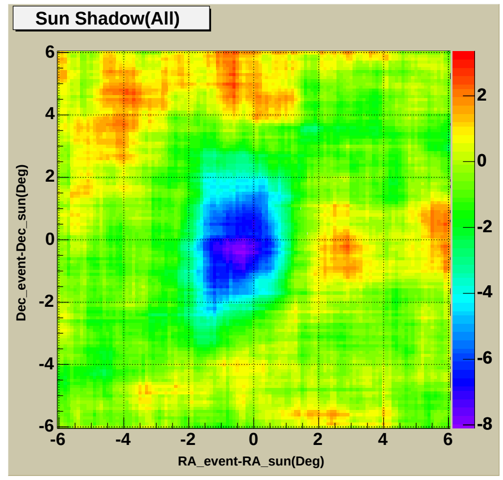

Fig. 2. The deficit significance map of the shadow of the sun

Milagro detector according to our Monte Carlo simulation result.

3.2. The shadow of the sun

Figure 2 shows the map of the significance of the deficit events near the sun for all data. The maximum deficit significance is -8.3σ and the fitted maximum deficit position is at (-0.34°±0.18°, -0.27°±0.21°). Figure 3 shows the map of the significances of the deficit events near the sun for the data taken when the earth is in the "away" and "toward" sectors of the IMF. The corresponding maximum deficit significances are -4.8σ and -6.4σ, and the fitted maximum deficit positions are at (-0.16° ± 0.36°,-0.03° ± 0.43°) and (-0.52° ± 0.29°, -0.42° ± 0.36°). If we substract the shift due to the geomagnetic field, the corresponding maximum deficit positions deflected by the solar magnetic field and the IMF are at (0.21° ± 0.18°,0.01°±0.21°), (0.39°±0.36°,0.25°±0.43°), and (0.03°±0.29°,-0.14°±0.36°). Though the northward and southward shifts of the shadows of the sun in the "away" and "toward" sectors of the IMF are consistent with that expected, given the statistical uncertainty in the measurement, the data is consistent with no shift of the shadow. The eastward shift of the shadow of the sun for all data is also consistent with no shift of the shadow within the statistical uncertainty in the measurement.

4. Summary

Analyzing Milagro gamma ray observatory data, we detected the moon shadow and the sun shadow with high significance. The shift of the shadow of the moon from its apparent position is consistent with that expected. The

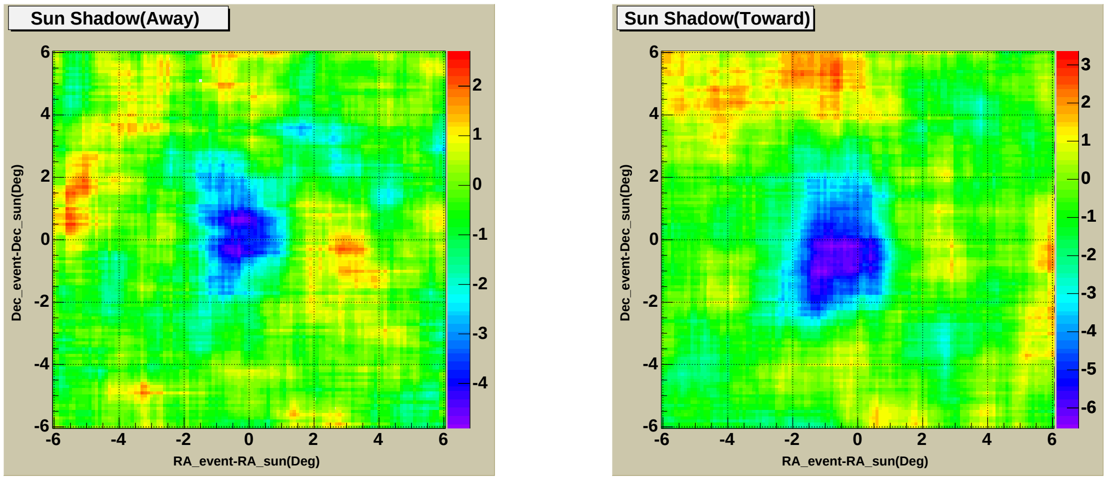

Fig. 3. The deficit significance map of the shadow of the sun in the "away"(left) and "toward"(right) sectors of the IMF

different shifts of the shadows of the sun in the "away" and "toward" sectors of the IMF are consistent with no shift of the shadows. The eastward shift of the shadow of the sun is also consistent with no shift of the shadow within the statistical uncertainty in the measurement.

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