Moon and Sun Shadowing Observed by the MACRO Detector

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Abstract

Using over 40 million muons collected since 1989 by the MACRO detector we have searched for a depletion of muons coming from the direction of the Moon due to primary cosmic rays striking the Moon. We observe this Moon shadow in the expected position with a statistical significance of more than 5 standard deviations. We have analyzed the same data for an analogous Sun shadow, and have found a signal with a significance of about 4 standard deviations. The Sun shadow is displaced from the Sun's position by about 0.6 degrees North in ecliptic coordinates. This displacement is compatible with a deflection of primary cosmic rays due to the Interplanetary Magnetic Field in the 10-20 TeV primary energy range which is relevant to the underground muons observed by MACRO.

1   Introduction:

MACRO was primarily designed to search for magnetic monopoles and rare particles in the cosmic rays, including high energy atmospheric neutrinos and muons from cosmic point sources (Ahlen et al., 1993). An important goal of the MACRO detector therefore is the recognition of point sources of high energy cosmic rays (E$>$ 10 TeV) by looking for an excess of underground muons from a particular direction of the sky and above a nearly isotropic background of cosmic rays. As previously suggested (Clark, 1957) the shadow in the high energy cosmic ray flux from the directions of the Moon and the Sun could be observed and employed to measure the angular resolution and pointing accuracy of the detector. Clear evidence of this effect has been reported by many EAS experiments (Aglietta et al., 1991, Alexandreas et al., 1991, Amenomori et al., 1993, Borione et al., 1994).

MACRO presented the first deep underground evidence of the Moon shadow effect (Ambrosio et al. 1999) and now presents evidence of the Sun shadow due to its excellent angular resolution ($\approx 1^{\circ}$) and its large collecting area and high statistics when compared to other deep underground detectors. Another very interesting point is that almost all cosmic ray particles are charged and deflected by Geomagnetic (GMF) and Interplanetary (IMF) magnetic fields. The shadows of the Moon and the Sun show these effects by means of displaced obscurations, whose analyses might give new information about these fields as well as about the cosmic-ray energy and charge distribution.

For this analysis we use the same technique used by Alexandreas et al., 1991, Amenomori et al., 1993 and Borione et al., 1994. In this work we extend the sample used for the previous Moon shadowing analysis (Ambrosio et al. 1999) and present the results for the Sun shadowing effect.

2   Event Selection:

The muon sample used in this study includes all events recorded between February 1989 and December 1998. About 45×10^6 events have been collected over 2.6×10^3 live days. The criteria used to select events for this analysis are the same as in Ambrosio 1999, defined to optimize the quality of reconstructed tracks. The selected events are consequently those which most accurately point back to their origin on the celestial sphere. These selection criteria reduce the sample size to 38.2×10^6 muons.

The topocentric positions of the Moon and the Sun are computed at the arrival time of each event in the sample, using the database of ephemerides available from the Jet Propulsion Laboratory, JPLEPH (Standish E.M. et al., 1995) and include a correction for the parallax due to MACRO's instantaneous position on the earth. The muon events in two 10° wide windows centered on the Moon and the Sun are selected for further analysis.

There are 3.17×10^5 events in the Moon window that pass all cuts. For the Sun shadow analysis there are 3.08×10^5 events collected that pass all cuts. Twenty five background samples are generated for each run used in the analysis. These backgrounds are constructed by coupling the direction of each muon in the run with the times of 25 randomly selected muons from the same run. The 25 background samples are then processed using the same procedure as the muon data sample.
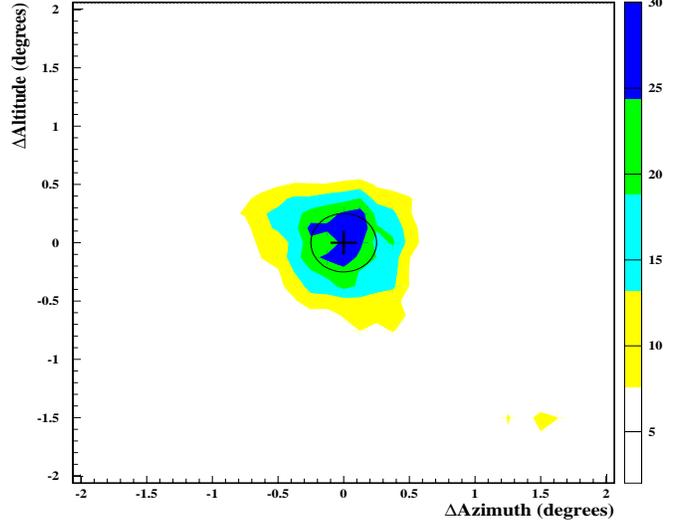
3 Shadow of the Moon:

The search for the Moon shadow in a direction-independent way and the estimate of its significance is possible with the maximum likelihood method of COS-B, a technique first described in detail by Cash W., 1979. This method is based on *a priori* knowledge of the point spread function of the MACRO detector (PSF). We have determined the PSF using the observed space angle distribution of double muons divided by $\sqrt{2}$. The PSF, as determined from more than 10^6 muon pairs, looks strongly peaked and has a non-Gaussian behavior (Ambrosio et al. 1999). To find the most likely position of the Moon, we compare the two-dimensional distribution of muons in the window centered on the Moon with the expected background events in the same window. In this analysis, each muon event is first sorted into a grid of equal solid angle bins ($\Delta \Omega = 0.125° \times 0.125° = 1.6 \times 10^{-2}$ deg^2). The shadowing source of strength S_M at a fixed position (x_s, y_s) that best fits the data is then found by minimizing

$$\chi^2(x_s, y_s, S_M) = 2 \sum_{i=1}^{n_{bin}} [N_i^{ex} - N_i + N_i \ln \frac{N_i}{N_i^{ex}}],$$

Figure 1: The two-dimensional distribution of λ in bins of equal solid angle in the Moon window. The axes are offsets from the Moon center. The fiducial position of the Moon, at position (0,0), is marked by a +; a circle corresponding to the average lunar radius, $0.26°$, is centered at this position. The λ grey scale is given at the right margin of the figure. The maximum of this distribution has $\lambda = 30.0$.

where the sum is over all bins in the window. Here N_i is the number of events observed in each bin i, N_i^{ex} is the expected number of events in bin i, and n_{bin} is the number of bins in the grid. This expression assumes that a Poissonian process is responsible for the events seen in each bin. The expected number of events in bin i is given by $N_i^{ex} = N_i^{bkd} - S_M \cdot \mathcal{P}(x_s - x_i, y_s - y_i)$, where N_i^{bkd} is the average number of background events at the position (x_i, y_i), and $S_M \cdot \mathcal{P}(x_s - x_i, y_s - y_i)$ is the number of events removed from bin i by the shadow of the Moon. Here $\mathcal{P}(x_s - x_i, y_s - y_i)$ is the MPSF, modified for the finite size of the Moon's disk, computed at the point (x_i, y_i) when the shadowing source is at (x_s, y_s). Finally, the shadow strength S_M that minimizes χ^2 is computed for every grid point in the window. This minimum $\chi^2(x_s, y_s, S_M)$ is then compared with $\chi^2(0)$ for the *null hypothesis* that no shadowing source is present in the window ($S_M = 0$), $\lambda = \chi^2(0) - \chi^2(x_s, y_s, S_M)$.

In Figure 1 we show the results of this analysis in a window $4.375° \times 4.375°$ centered on the Moon. This window has been divided into 35×35 cells, each having dimensions $0.125° \times 0.125°$. In this window the number of muon events is of 14388. In this figure, λ is displayed in grey scale format for every bin in the Moon window.

Also shown is the fiducial position of the Moon and a circle centered at this position corresponding to the average lunar radius, $0.26°$. The maximum $\lambda = 30.0$, corresponding to 5.5σ, is found at the expected Moon

position and this provides further confirmation of MACRO's absolute pointing. The value of the shadow strength obtained by the likelihood method at this position, $S_M = 243^{+31}_{-41}$ events, agrees well with the expected value of 215 events. We have verified the properties of the λ distribution by constructing 71 other windows similar to the Moon window, each displaced from the next by $5°$ in right ascension. For each off-source window, we have followed the procedure used for the Moon window in computing the expected background. To avoid edge effects associated with a source near the edge of a window, we only have evaluated λ for the central 12×12 bins.

4   Angular Resolution of the MACRO Apparatus:

If we assume that the space angle distribution of double muons is a good approximation of PSF, the angular resolution of the apparatus can firstly be estimated by this distribution as the angle $\theta_{68\%}$ of the cone that contains the 68% of the events from a point-like source. Using this definition of the angular resolution, we obtain $\theta_{68\%} = 0.8°$. Since a simple Gaussian function cannot fit the PSF, we cannot compute the angular resolution as the σ of the Gaussian function that maximizes the likelihood function for the detection of the Moon shadow. Therefore we define a scale parameter $\mathcal{F}$ that rigidly scales the PSF by the factor $\mathcal{F}$, $\tilde{\mathcal{P}}(x_s - x_i, y_s - y_i; \mathcal{F})$ and then repeat the likelihood analysis in the Moon window for different values of $\mathcal{F}$. We assume that the value of $\mathcal{F}$ that maximizes λ gives the best $\mathcal{F}$ for computing the angular resolution. Using these procedure we find that the angular resolution is $0.86°\,^{-0.18°}_{+0.26°}$ fully consistent with the other estimation.

5   The Sun Shadow:

We have repeated the same analysis by using events in the Sun window. In ecliptic coordinates (ecliptic latitude and ecliptic longitude), the maximum-likelihood method gives a map of λ, in the Sun window, as shown in Figure 2. The most probable position of the center of the deficit is found at $(0°,0.625°)$ with a λ=17.4 corresponding to a significance of 4.2 σ. The probability to find random fluctuations having a $p(\chi^2 \geq 17.4)$ is less than 10^{-5}, hence the observed Sun's shadow is significant.

The large displacement of the shadow from the apparent position of the Sun is likely due to the combined effect of the magnetic field of the Sun and the geomagnetic field. However a quantitative interpretation of the Sun's shadow in connection with the effect of the solar magnetic field is difficult, because during almost ten years of MACRO data acquisition, the effect of the IMF is averaged over its changes due to the variable inclination and over the yearly variation of solar activity with a period of 22 years. Moreover the IMF has a sector structure with the magnetic field direction reversed so that in some sectors the magnetic field points inwards and in others outwards and the neutral sheet separating the two regions is in-
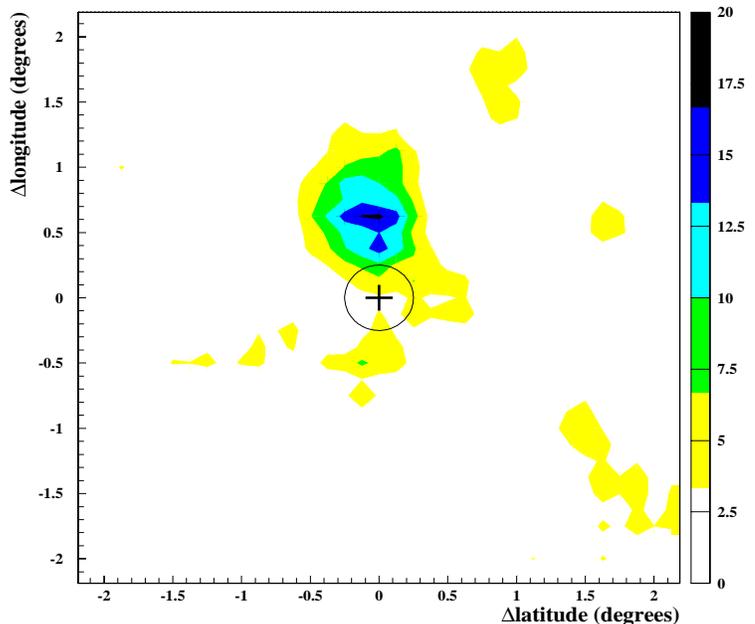
Figure 2: The two-dimensional distribution of λ in bins of equal solid angle in the Sun window. The axes are offsets from the Sun center using ecliptic coordinates. The fiducial position of the Sun, at position (0,0), is marked by a +; a circle corresponding to the average solar radius, $0.26°$, is centered at this position. The λ grey scale is given at the right margin of the figure. The maximum of this distribution, $\lambda = 17.4$, is about $0.6°$ N .

clined to the equatorial plane. As the earth is within $7°$ of the solar equatorial plan, the polarity of the IMF will change several times during the Sun rotation of 27 days on its axis.

A careful selection of the data as a function of IMF polarity configuration, as well as higher statistics, could be used to obtain new information about the IMF.

6   Conclusions:

The MACRO detector, operational since February 1989, has collected a muon sample of about 40 million events. Using this sample we have observed the Moon and Sun shadows in the cosmic ray sky at primary energies $\approx$ 10 - 15 TeV. In the deficit analysis, we find an event deficit around the Moon of about 5.0σ significance. With a maximum likelihood analysis, we confirm the detection of the Moon's shadow with a significance of 5.5σ. Our estimate of the angular resolution is $\theta_{68\%} = 0.86°{}_{+0.26°}^{-0.18°}$. These results characterize MACRO as a muon telescope by confirming MACRO's absolute pointing ability and by quantifying its angular resolution. This investigation shows that the MACRO detector has the capability of detecting signals from point-like sources by detecting secondary underground muons . The analysis of the deficit in the Sun direction and in ecliptic coordinates gives a Sun shadow with a significance of 4.2 σ. The shadow of the Moon and the Sun is shifted due to the curvature of cosmic rays by GMF and IMF at the primary energy of 10-20 TeV relevant to MACRO.

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