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BRIEF REPORTS

Brief Reports are accounts of completed research which do not warrant regular articles or the priority handling given to Rapid Communications; however, the same standards of scientific quality apply. (Addenda are included in Brief Reports.) A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.

Observation of shadowing of ultrahigh-energy cosmic rays by the Moon and the Sun

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Data from an extensive air shower detector of ultrahigh-energy cosmic rays shows shadowing of the cosmic-ray flux by the Moon and the Sun with signficance of 4.9 standard deviations. This is the first observation of such shadowing. The effect has been used to determine that the angular resolution of the detector is $0.75^\circ\ ^{+0.13^\circ}_{-0.09^\circ}$.

I. INTRODUCTION

Our collaboration has been conducting, since 1986, an extensive air shower (EAS) experiment with the goal of observing emissions from discrete sources in the Galaxy. Since neutral particles, such as γ rays, are undeflected by galactic magnetic fields, it is expected that they will reveal the location and nature of their sources. Recent observations of γ rays from compact binary systems have raised the exciting prospect that a site of acceleration of ultrahigh-energy (UHE) cosmic rays (charged particles and nuclei) may be in these systems. Establishment of this would be a significant step in our understanding of cosmic radiation.[1]

To observe point sources, neutral particles emitted from them must be detected above the nearly isotropic background of ordinary cosmic-ray protons and nuclei. For a point source, the signal/background ratio is in inverse proportion to the square of the angular resolution. Therefore, a critical feature of an EAS detector system is its angular resolution.

Our apparatus samples the particles in the cascade with an array of scintillator detectors. Both the particle count and the relative arrival time are measured by each detector. The arrival times, measured to ~ 1 ns, are used to determine the direction of the primary-cosmic-ray particle.

We have previously reported episodic emission from Cygnus X-3 and Hercules X-1,[2,3] but as of yet we have found no sources which are steadily emitting UHE γ rays.[4] In each case, the method used to analyze the signal, or set a limit on the flux, requires knowledge of the actual angular resolution. Because the signal we detected contained an insufficient number of events to determine the angular resolution, and because of the general paucity of signals, it is important to verify that the apparatus was actually operating with the estimated angular resolution, and that no significant systematic "pointing" errors were present.

It was originally proposed by Clark[5] that the shadow of the Moon and the Sun could be observed with high-energy cosmic rays. Since the Moon and Sun each have an angular radius of approximately 0.26°, and since the expected angular resolution of the apparatus is approximately 0.7°, we should be able to observe a reduction in the detected cosmic-ray intensity due to shadowing. However, a large sample of events is necessary to obtain a statistically significant result, because the dip in intensity is small.

The magnetic field of the Sun causes some deflection of charged cosmic rays. For 50-TeV protons, the Sun's shadow is slightly distorted and is displaced by less than 0.15° assuming the Sun's magnetic field is a dipole with a strength of 1 G at the surface of the solar equator.[6] We have neglected magnetic deflection in this analysis, since it is much smaller than the angular resolution of the detector.

II. ESTIMATES OF THE ANGULAR RESOLUTION

Previously, the angular resolution was estimated by (a) subdividing the array into two subarrays and (b) computer simulations. We have also used measurements of shower muon directions in a shielded tracking detector to study systematic pointing errors. These methods and results are summarized here; somewhat more detailed descriptions have been given elsewhere.[7,8]

Using method (a), the set of struck detectors for each shower is divided into two subsets, and the arrival direction is computed independently for each. The distribution of the angle differences between subsets is used to estimate the overall angular resolution. It gives an average angular resolution of about 0.8°, neglecting any systematic errors common to both subarrays. The resulting resolution may vary by 0.1° depending on the way the subarrays are chosen. The distribution of angle differences is approximately what would be obtained from a Gaussian density.

Method (b) relies on Monte Carlo simulations of the detection and digitization processes using observed time and particle detector responses. These indicate that the angular resolution is approximately 0.7°.

Systematic pointing errors were evaluated by comparing the EAS arrival direction with the direction of shower muons measured in a 12 m^2 tracking detector that was operated together with the array for approximately 2 years. By studying distributions of the difference in projected angles measured by the tracking detector and the array, it was possible to estimate the maximum systematic error between the two measurement methods; this was approximately 0.2°. The width of these distributions was consistent with the angular resolution obtained with methods (a) and (b).

III. DATA

The data used in this search for the shadow of the Moon and Sun comprise 108 $\times 10^6$ showers recorded over the interval April 1986 to February 1990.[9] Over this interval, the trigger rate has increased from $\sim$0.5 sec^{-1} to $\sim$4 sec^{-1}, due to an increase in the number of scintillators, and a lowering of the trigger threshold. In this analysis, the geocentric right ascension α and declination δ of the Moon was computed using an algorithm by Van Flandern and Pulkkinen;[10] formulas from the Astronomical Almanac[11] were used to compute α and δ of the Sun. Over the time interval of interest both determinations have been verified to agree with the tabulations of these quantities given in the Astronomical Almanac to within 0.05°. Corrections for parallax were made to the Moon coordinates.[12] The angles between each shower arrival direction and the Moon and Sun were computed.[13]

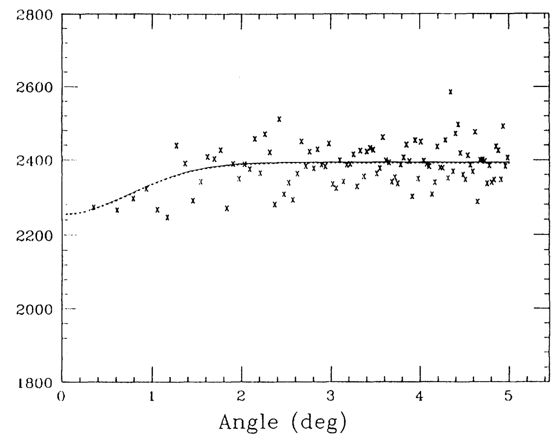

FIG. 1. The angular density of events vs angular displacement from the center of the Moon or Sun for 238 389 showers with arrival direction within 5° of the Moon or Sun. The solid curve is the density predicted for a Gaussian angular resolution with standard deviation of 0.75°.

We now consider the subset of 238 389 events within 5° of the Moon or within 5° of the Sun. The majority of events in the data set (154 051) are near the Moon. This is due to the strong dependence of the sensitivity of the detector on the (local) zenith angle of the shower, which favors the Moon, particularly during the winter, when the most recent data were recorded.

Figure 1 shows the angular density, $dN/d\Omega$, as a function of the angular distance from the Moon or Sun.[14]

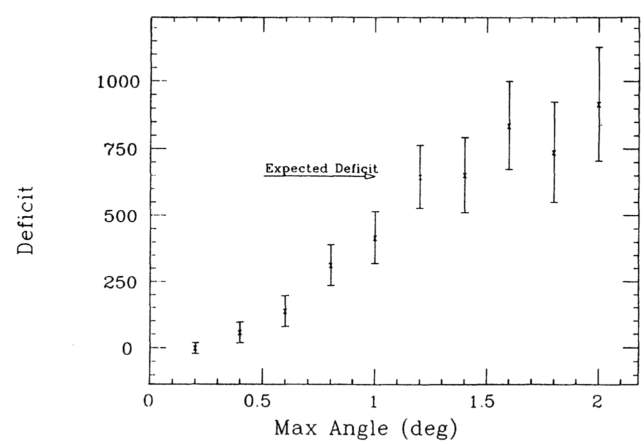

FIG. 2. The deficit (defined in the text) for the Moon and Sun data as a function of the maximum angle. The total expected deficit is also indicated. Note that, because the deficit is an integral out to the maximum angle, the points in the graph are statistically correlated.

The shadowing is evident in this figure. Before considering the shape of the dip, it is possible to verify that its depth is correct. The measured density between 2° and 5° from the Moon or Sun, where shadowing is negligible, is used to calculate the expected number of events close to the Sun and Moon. The difference between this number and the number of observed events within an angle β from the center determines a "deficit," or number of missing events. Figure 2 shows this deficit for the combined Moon and Sun data. The absolute value of the deficit is determined by the measured density and the angular sizes; the measured deficit is seen to be in statistical agreement with expectations.

It reaches a plateau near 1°, as expected for an angular resolution of $\sim 0.7°$. The statistical significance of the deficit depends on the assumed angular resolution. Using our previous estimates of our angular resolution, the significance of the deficit can be seen to be between 4.5 to 5 standard deviations. A background sample of 393 112 events offset from the Moon or Sun was treated in the same manner; no significant deficit was obtained.

IV. DETERMINATION OF THE ANGULAR RESOLUTION

The shape of the angular density distribution is sensitive to the angular resolution of the detector. We describe here a use of the maximum-likelihood method[15] to estimate the resolution. The method requires *a priori* knowledge of the resolution function; we assume that it is a two-dimensional Gaussian distribution. Studies of the data support this hypothesis, and also indicate that the width σ of the Gaussian is a function of the number of detectors struck by the shower particles. In this analysis, we neglect this dependence, and the resulting estimate of σ is for an average over the distribution of struck detectors.[16]

The probability used to construct the likelihood is most conveniently written in terms of a scaled variable z

$$z = \frac{1-\cos(\beta)}{1-\cos(\beta_{\max})} , \tag{1}$$

where β is the angle between the shower arrival direction and the Moon or the Sun. The distribution of z can be shown to be

$$\frac{dP}{dz} \propto 1 - \frac{\beta_{\rm MS}^2}{2\sigma_1^2} e^{-\beta(z)^2/2\sigma_1^2} , \tag{2}$$

where $\beta_{\rm MS}$ is the angular radius of the Moon or Sun,[17] and σ_1 is approximately equal[18] to σ. The likelihood is the product of the normalized probability dP/dz for each event in the sample. The normalization of the probability ensures that the likelihood will have a maximum at the correct σ if there is shadowing in the data.

The likelihood has been computed numerically for many trial σ's, both for the combined Sun and Moon data and for the background data; its natural logarithm is plotted against trial σ in Fig. 3. The curve for the data

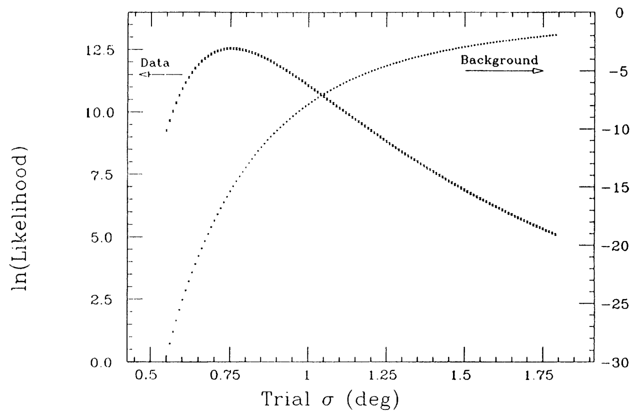

FIG. 3. The natural logarithm of the likelihood as a function of the trial sigma for the Moon and Sun data set, and for the background data set.

shows a maximum at 0.75°, the background at greater than 1.75°. For a flat background, the likelihood is expected to maximize at a large σ, and to become very small at small σ. The statistical significance of the result can be estimated using the Gaussian approximation, for which the "number of standard deviations, " N_σ is

$$N_\sigma = \sqrt{2(w_{\rm max} - w_\infty)} ,$$

where $w_{\rm max}$ and w_∞ are the natural logarithm of the likelihood for the trial σ which maximizes the likelihood, and for a very large σ. For these data, we find

$$N_\sigma = 4.9 .$$

If we take as the uncertainty in σ the interval between w at its maximum and where the value of w has decreased by 0.5, then the result may be stated as

$$\sigma = 0.75° {}^{+0.13°}_{-0.09°} .$$

This analysis was repeated separately for the 154 051 events in the Moon data set; the result was $\sigma = 0.80° {}^{+0.17°}_{-0.12°}$.

In addition, to the likelihood analysis, a least squares fit of the angular distribution was made to Eq. (2). For 25 angular bins, out to 5°, χ^2 is a minimum[19] for $\sigma = 0.76°$.

V. RANDOM AND SYSTEMATIC ERRORS

The results obtained on our angular pointing error from the Moon and Sun shadow analysis may be combined with our previous estimates of our random pointing error to constrain the possible systematic errors. To explore this, we have considered the effect of a systematic "pointing" error superposed on the random errors. A numerical calculation of the density of the shadow, i.e., the second term on the right-hand side of Eq. (2), was made assuming a Gaussian random error distribution with σ of 0.7° and a systematic offset. The rms radius of the shadow was then computed. For systematic offsets of less than 0.5°, the rms radius is close to the assumed random error σ; its value is within 9% of what would be obtained by adding the offset and the random error σ in quadrature. For larger offsets, the rms radius is dominated by the offset.

The shadowing result for σ obtained above would admit a systematic error of up to approximately 0.6°. Systematic errors much larger than 0.6° require random errors to be significantly smaller than we have estimated with methods (a) and (b).

VI. CONCLUSIONS

The shadowing of the high-energy charged cosmic-ray background by the Moon and Sun has been clearly observed. The statistical significance of the shadow observation is 4.9 standard deviations. We believe this is the first such observation. The magnitude of this effect agrees with expectations. The mean angular resolution of the apparatus as determined by analysis of the shape of the occultation is $0.75° {}^{+0.13°}_{-0.09°}$. This is in agreement with our previously published estimates.

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[9]This interval contains a block of data, from March to November 1988, which is not yet fully processed, and is not included in this analysis.

[10]T. C. Van Flandern and K. F. Pulkkinen, Astrophys. J. Suppl. Series **41**, 391 (1979).

[11]*The Astronomical Almanac for the Year 1989* (U.S. Government Printing Office, Washington, D.C. /Her Majesty's Stationery Office, London, 1989).

[12]See Ref. 11, p. D3.

[13]The α and δ of each event are normally computed in epoch 1950. For this comparison, they are precessed to the event date.

[14]We have found that the fluctuations of the data are somewhat larger than those expected from Poisson statistics; we attribute this to the finite granularity (0.1 degree) of the arrival direction angles stored in the database used for this study.

[15]The general method is described by Frank T. Solmitz, Annu. Rev. Nuc. Sci. **14**, 371 (1964). The formulas for the uncertainty in resolution and for the significance are from the Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, 1 (1988).

[16]Monte Carlo simulations of this data analysis have revealed that, for our angular resolution and size of data set, including the dependence on the number of detectors struck does not substantially change the result.

[17]This distribution corresponds to a flat (isotropic) background depleted by a Gaussian shadow. The observed density of events is actually a strong function of the zenith angle. But, as indicated by the background data set, the density as function of the angle from the Moon or Sun center is uniform.

[18]The difference between σ_1 and σ is less than 0.02° for σ greater than 0.5°; the correct value of σ_1 is used in the analysis.

[19]The value of χ^2 at minimum is 33.88; for 23 degrees of freedom the probability of exceeding this is 5.1%. This somewhat low probability is associated with the granularity noise mentioned above. The χ^2 probability for no shadow is 7.5×10^{-5}.