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Angular resolution of GRAPES-3 array obtained from the shadow of Moon and Sun in extensive air showers

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Abstract: The GRAPES-3 experiment observes extensive air showers using a high-density array of scintillation detectors and a large area tracking muon detector. The array consists of 300 scintillation detectors (each $1m^2$ in area) and 16 modules of muon detector having a total area of $560m^2$. Good angular resolution of the array is a key requirement for detection of point sources of gamma rays. Since the angular size of Sun and Moon are small compared to the expected angular resolution of our array, we have used the deficit in shower rate caused by the shadow of these two objects to determine the angular resolution as a function of shower size. Here we report the results of our analysis on observation of the shadow of Moon and Sun.

Introduction

GRAPES-3 experiment is a wide field of view gamma ray observation operating at Ooty (E76.7°, N11.4°, 2200m asl), India. Mean atmospheric depth at Ooty is about $800g/cm^2$. The array of scintillation detectors observes the distribution of secondery particles in the extensive air showers to reconstruct the direction and energy of the primary particles and 16 large area muon detectors measure the muon content accompanying the air showers. The array of 256 scintillation detectors is operating with trigger rate of 13Hz in the period used in this analysis (Figure1).

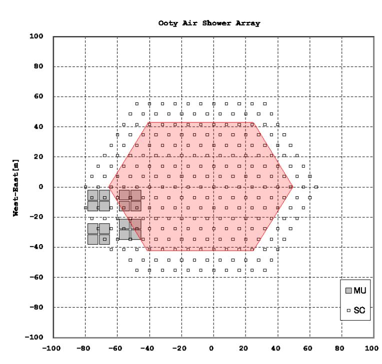

Figure 1: GRAPES-3 air shower array in the period of 2000 - 2003. 256 scintillation detectors and 16 large area muon detectors

One of the most important goal of GRAPES-3 experiment is the search for gamma ray point sources. We must know the angular resolution of the array, because if the array has the better angular resolution, the smaller region around sources will be required to search thus the lower background. High energy primary cosmic rays produce extensive air showers in the atmosphere and are detected by the array of scintillation detectors when a suitable trigger condition is satisfied. Because the threshold energy of primary cosmic ray particles detected by GRAPES-3 air shower array is a few TeV, all extensive air showers detected are originated from extragalactic primary cosmic rays passing through the solor system in the the almost straight line. So we can expect to see the shadow of the Moon and Sun in the isotropic distributed air showers induced by those primary cosmic rays when we observe the area around the Moon and Sun both spreading with $0.5°$ diameter on celestial sphere. The observation of the shadow of Sun and Moon is usefull way to know the angular resolution directly of air shower array. Here we report on the results of the analysis of the shadow of Moon and Sun.

Method

We used the equal solid angle method to observe the shadow of the Moon and Sun. The center of the circular search window with radius of $4°$ was set on the Moon/Sun, and the search area was devided into several bins of annuli each having same solid angle (Figure2). If the angular resolution of array is good, the shadow of the Moon and Sun appears as a clear deficit of shower rate at the center of search area. But for the Sun shadow, it is difficult to see a clear deficit in this method because that the shape of the Sun shadow and its position is affected by the magnetic field of the surface of the Sun. This method can't follow such an irregular shape of the Sun shadow.

We selected another region on the sky as a background area where there is no object preventing the cosmic rays from reaching earth. The background region was placed by rotating the actual Moon/Sun position by $\pm 8°$ in the azmuth direction with the same search window. Two backgrounds located at symmetrical place with respect to the actual Moon/Sun position were added togather to be a background data.

Event selection

To select properly reconstructed showers we applied some quality cuts for both the Moon and Sun

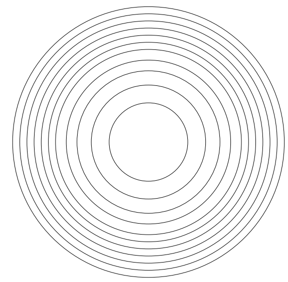

Figure 2: Circular search window used in this analysis. Each annuli has same solid angle. Moon/Sun is on the center of this area.

analysis. Ratio of number of particles detected in the outer 2 rings of scintillation detecter array to a total number of particles should be less than 0.35 for the purpose that the shower core was estimated properly. The estimated shower core must be inside the hexagonal area masked with red color in the Figure1. The zenith angle of reconstructed air shower direction is required to be less than $40°$. The data which seems to have noisy counters was removed from analysis. And the data set with an amplitude of azimuthal angle distribution of more than 1.5% was not used in this analysis, because the angular resolution is not good in that period.

The data set in this analysis was recorded between 2000 March and 2003 May. After applying all cuts, the total number of events for the Moon becomes 5.7×10^5 and for the Sun becomes 7.3×10^5. Furthermore we removed the data in the period 2000 - 2001 from the Sun shadow analysis, because in that period the solor magnetic field is so strong that we couldn't see the shadow of the Sun in the equal solid angle method. Finally 3.8×10^5 events remained for the Sun.

Shadow of the Moon

In the Figure3 the shadow of the Moon appears as a deficit of number of events at the center of search area. The flat back ground in the bottom figure in which the no deficit can be seen indicates the deficit of the shadow of the Moon is not artifact.

Figure4 shows the dependence of the angular resolution on the shower size. The angular resolution of thr air shower array improves as the shower size increase.

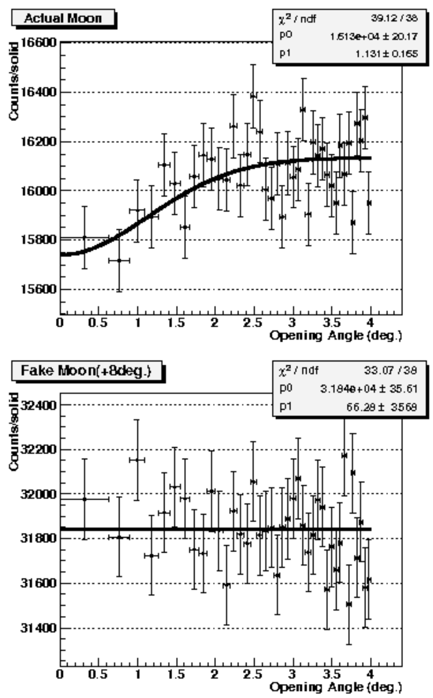

Figure 3: Top: Shadow of the Moon. Bottom: Background. Each bin in the figure has same solid angle. Angular resolution was calculated to be 1.13° for the shower size of log10(Size) $\geq$ 3.2. The two back ground regions were added togather.

Shadow of the Sun

As mentioned above, we removed the data set in the period of 2000 - 2001, because the solor magnetic field in this period was strong that affects the shadow of the Sun so that we couldn't see the shadow of the Sun and measure the angular resolution properly. The shadow of the Sun is shown in the Figure5 with the back ground area. The calculated angular resolution is 0.75° for the shower size of log10(Size) $\geq$ 4.25. The angular resolution derived from the Sun shadow is large compared to the Moon whose resolution is 0.52° for the same shower size condition, this may be due to the effect of the solor magnetic field.

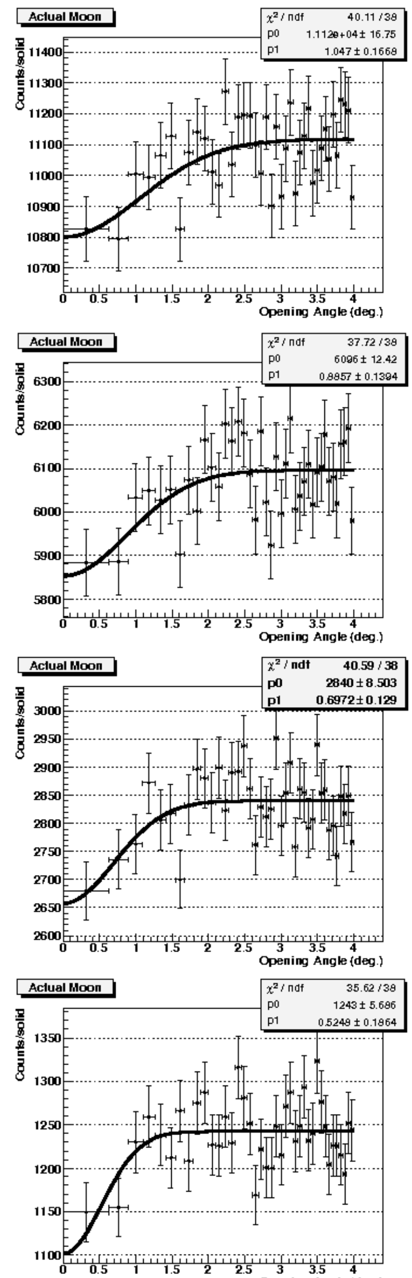

Figure 4: Shadow of the Moon. From top the shower size of log10(Size) $\geq$ 3.5, $\geq$ 3.75, $\geq$ 4.0, $\geq$ 4.25. The angular resolution is 1.05°, 0.89°, 0.70°, 0.52° respectively.

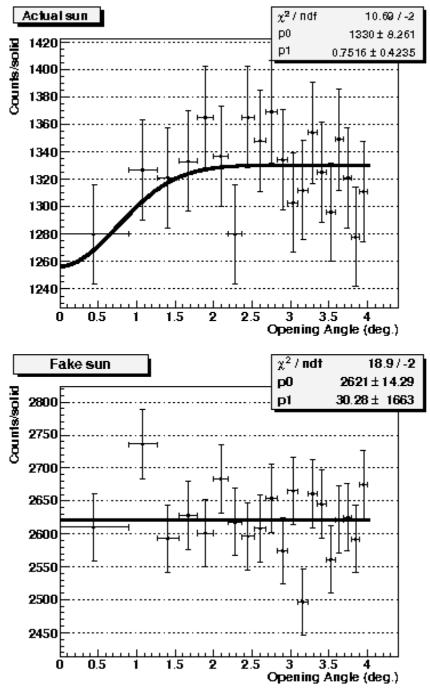

Figure 5: Shadow of the Sun with the shower size of log10(Size) $\geq$ 4.25. The angular resolution was calculated to be 0.75°.

Summery

We have observed the shadow of the Moon and Sun using extensive air showers. The angular resolution of the array for the shower size of $\geq$ 3.2 is about 1.13° which will be used for the point source analysis[1]. We adopted the angular resolution derived from the Moon shadow analysis as the angular resolution of the air shower array, because in the Sun shadow analysis the data in the period of high solor activity was not used and it seems that the influence of the solor magnetic field on the shadow of the Sun is still remained even after removing such the data set. So we concerned the Sun shadow to be just an indicator for the validity of the Moon shadow analysis.

Acknowledgements

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