Study of the GRAPES-3 sensitivity to Crab nebula with expanded muon detector

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***Abstract*. The huge cosmic ray background and extremely low signal primarily limit the sensitivity of the EAS experiments for UHE γ-ray astronomy. However the GRAPES-3 high density EAS array has a unique advantage for UHE γ-ray astronomy as it uses muon detection for cosmic ray back ground rejection using a large area ($560m^2$) compact tracking muon detector. To increase background rejection efficiency further, it was decided to increase the muon detector area to $1120m^2$ by constructing another muon detector similar to the existing one. Here we present the results of the Monte Carlo simulation study of the rejection efficiency and sensitivity detection of CRAB nebula with the expanded muon detector. The simulation results show that the CRAB nebula can be seen unambiguously in 1 year with the expanded muon detector.**

***Keywords*: GRAPES-3, Rejection Efficiency, Crab nebula sensitivity**

I. Introduction

The origin of cosmic rays (CRs) is an open problem and the study of γ-ray sources at TeV to PeV energy range is expected to provide vital information on this question. The detection of several γ-ray sources in the TeV energy region in last few years due to the advanced ground based telescopes using imaging atmospheric Cerenkov technique (IACT) is generating a lot of excitement in the field of TeV γ-ray astronomy. However these telescopes are optimized for 100 GeV to 10 TeV energy range[1]. On the other hand the extensive air shower (EAS) arrays with particle detectors are generally sensitive above 10 TeV. In addition, the EAS arrays have very large field of view and operate all the time, where as IACT telescopes have narrow field of view and only operate 8-10% of time. Thus EAS arrays can observe multiple sources at the same time and can be used as search instruments. However, not many statistically significant detections have been observed by EAS arrays mainly because of two reasons; (1) extremely low γ-ray flux above 10 TeV due to steeply falling spectrum and (2) large CR background. CR background become more dominant over the signal in the case of EAS arrays due to poorer angular resolution.

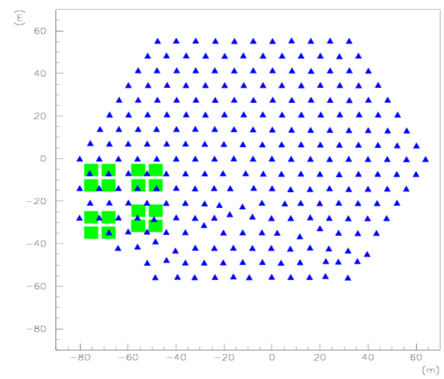

Fig. 1: Schematic of the GRAPES-3 array. The scintillator detectors are shown by $\triangle$s and the muon detector modules were shown by s

A good angular resolution and a high CR background rejection is required to increase the sensitivity of EAS arrays which may be understood from the following expression. The significance of detection with events observed in an area A and for a time period of T, with background rejection may be expressed as

$$\sigma = \frac{SignalEvents}{\sqrt{BackgroundEvents}} = \frac{ATF_\gamma}{\sqrt{ATF_{CR}\Omega(1-\epsilon_{rej})}} \quad (1)$$

Where F_γ is the integral γ-ray flux from the source, F_{CR} is the integral cosmic ray flux, Ω is solid angle of acceptance of events (Ω=$\pi\theta^2$, where θ is the half angle of the cone around the source) and ϵ_{rej} is the rejection efficiency of CRs. The value of θ is generally taken to be 1.6 times the angular resolution of the experiment. The equation implies that the significance is inversely proportional to the angular resolution and improves with ϵ_{rej} as $\sqrt{\frac{1}{1-\epsilon_{rej}}}$. For example even 90% rejection efficiency can give 3.3 times higher significance than without any rejection. Therefore it is very important to achieve high rejection efficiency.

Though there are different methods for CR background rejection, however the rejection by distinguishing a CR induced shower from a γ-ray induced shower based on the muon content is known to be the most efficient method used by EAS arrays. This is because of γ-ray induced shower contains fewer muons as compared to a CR induced shower. Hence the muon poor showers are likely to be due to γ-ray induced showers. Therefore EAS arrays equipped with muon detectors have an advantage for CR background rejection. In a typical CR shower, muons constitute about 10% of the total shower particles and spread laterally to several hundred meters from the shower core. The density of muons falls with increasing distance from the core. Therefore even for a CR induced shower, if the core lands at a large distance from muon detector, very few or no muon could be detected depending on the area of the muon detector and such showers would be be treated as a γ-ray induced. Hence the efficiency of identifying and thus rejecting CRs based on the muon content would reduce with increasing distance of the shower core from the muon detector. As the signal events are proportional to the area over which the events are selected, events with core up to a large distance from the muon detector need to be selected to maximize the number of signal events. At same time the rejection efficiency need to be high for larger core distances to maximize the signal to background ratio. High rejection efficiency to larger core distances can be achieved by increasing the muon detector area.

II. The GRAPES-3 Experiment and the expanded muon detector

The GRAPES-3 EAS experiment is located at Ooty, India at a latitute of 11.4^o N and longitude 76.7^o E. UHE γ-ray astronomy is one of its primary goal. Being located close to the equator, the GRAPES-3 has a good overlap of the sky with the experiments located both in the northern hemisphere such as the MILAGRO and the southern hemisphere such as the HESS. The GRAPES-3 can look for the already observed sources, but at a higher energy. The GRAPES-3 is a dense array of 400 scintillator detectors with 8 meter separation between detectors and the details of the experiment is described elsewhere [2]. Because of small detector separation, the GRAPES-3 can detect showers below 10 TeV. The trigger efficiency is 90% for γ-ray showers at 30 TeV and for proton showers at 50 TeV. The array is equipped with a large area ($560m^2$) compact muon detector with 16 modules each of area $36m^2$ [3]. Because of the large area muon detector, the GRAPES-3 is ideal for doing UHE γ-ray astronomy.

Since larger area muon detector is preferable for achieving higher background rejection as discussed in section I, it is proposed to add another $560m^2$ area muon detector similar to the existing one. Hereafter, we refer the present muon detector by PMD and the expanded muon detector (present + proposed) by EMD. Prior to the construction of the proposed muon detector, it was decided to carry out Monte Carlo simulations to measure the advantages of the proposed detector. In the simulations, we calculated the rejection efficiency for both the PMD and the EMD as a function of the core distances. Next we have estimated the significance from a standard γ-ray source i.e. Crab nebula for the PMD and the EMD.

III. Simulation of cosmic ray showers

Showers of proton primary were simulated using air shower simulation code CORSIKA (Version 6.60) [4] with VENUS hadronic interaction model [5]. The [5] showers were simulated from 50 to 1000 TeV using a power law spectrum of spectral index -2.7. Energy cut of 1 GeV is placed for muons which is also the threshold energy of the muon detector. A total of 19000 events were generated. The CORSIKA output binary data were read and stored in a ROOT tree structure for subsequent analysis.

IV. Calculation of Rejection Efficiency

The rejection efficiency ϵ_{rej} for PMD was first calculated as a function of distance of the shower core from the muon detector center (R_{core}) by throwing the core of the showers randomly on the circumference of the concentric circles drawn around the center of the muon detector with 1 meter increment in radius at a time. The original coordinates of the particles of the shower were shifted with respect to the the new random core position. For the given R_{core}, for each shower the number of muons which fall within muon detector area were assumed to have been detected and counted. The distribution of the detected muons N_μ so called muon multiplicity distribution for the sample of 19000 showers for four different core distances is shown in Fig. 2a-d. The mean value of N_μ was calculated and found to be 25.5, 15.0, 7.6, 3.4 for R_{core} = 10m, 25m, 50m and 100m respectively. Hence the number of showers detected with no muon in the first bin in Fig. 2 increases with R_{core}.

ϵ_{rej} for a given R_{core} was calculated as follows

$$\epsilon_{rej} = \frac{\Sigma_{N_{\mu >=1}} N_\mu}{N_{total}} \tag{2}$$

Where N_{total} is total number of showers.

ϵ_{rej} was calculated for different R_{core} up to 100 meters and presented in Fig. 3 as a function of R_{core}. The lower curve in the figure is for the PMD and upper curve is for the EMD. For the PMD ϵ_{rej} is close to 100% for first few meters and remains above 99% upto R_{core} $\sim$ 25 meter and thereafter a faster decrease is seen. For the EMD ϵ_{rej} remain above 99% upto $R_{core} \sim$ 50 meter. This implies showers above 99% ϵ_{rej} can be selected with 4 times larger area with the EMD compared to the PMD.

V. Estimation of significance from Crab nebula

Each term given in equation. 1 was calculated to estimate the significance from Crab nebula.

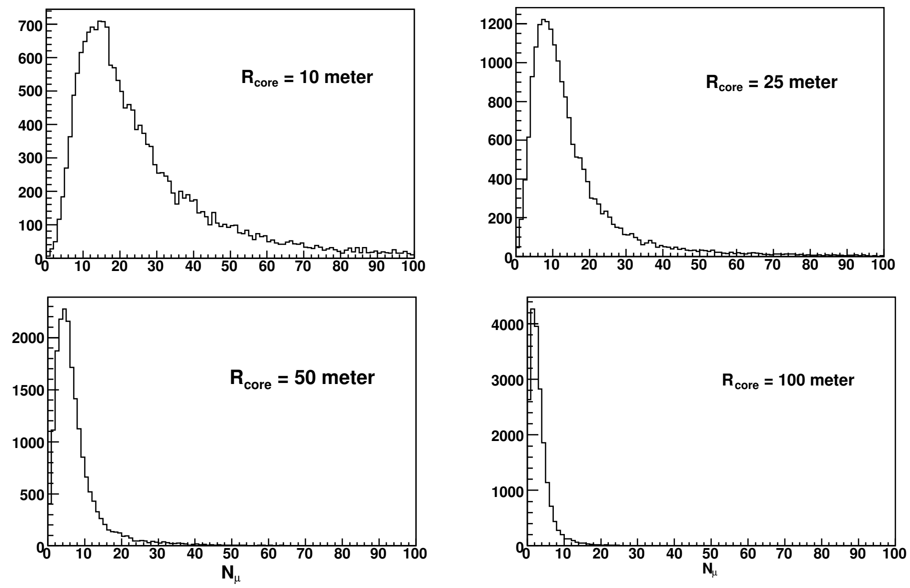

Fig. 2: Muon multiplicity distribution for 4 different core distances. First bin in the distribution corresponds to no muon

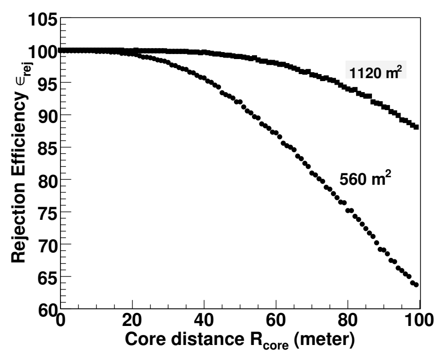

Fig. 3: Rejection efficiency as a function of core distance of the showers from center of the muon detector. The upper curve is for the expanded muon detector and the lower curve is the for the present muon detector

As same trigger efficiency (90%) is achieved by γ-ray showers of energy 30 TeV and proton showers of energy 50 TeV, hence the integral γ- ray flux F_γ from the CRAB nebula was calculated above 30 TeV to 1000 TeV using the differential flux $\frac{dF_\gamma}{dE} = 3.3 \times 10^{-7} E^{2.57} m^{-2} sr^{-1} s^{-1} TeV^{-1}$ measured by the HESS experiment.

$$F_\gamma = 10^{-9} m^{-2} s^{-1} \tag{3}$$

The integral cosmic ray flux F_{CR} for proton primary was calculated above 50 TeV to 1000 TeV using differential flux $\frac{dF_{CR}}{dE} = 0.1057 \pm 0.003 E^{2.76\pm0.02} m^{-2} sr^{-1} s^{-1} TeV^{-1}$ obtained from the direct measurements.

$$F_{CR} = 6.15 \times 10^{-5} m^{-2} sr^{-1} s^{-1} \tag{4}$$

TABLE I: Actual background events, retained background events after rejection, signal events and the significance from CRAB nebula for the area bounded by different core distances

R_{core}	A (m^2)	Actual BG	BG after Rej.	γ's	σ
10	314	248	0	1	29.1
20	1257	995	0	5	10.9
30	2828	2240	1	13	10.4
40	5027	3982	6	23	9.3
50	7855	6222	22	36	7.6
60	11311	8960	65	52	6.5
70	15396	12196	160	71	5.6
80	20109	15930	340	93	5.0
90	25450	20162	652	117	4.6
99	30795	24396	1098	142	4.3

The circular area A for each core distance R_{core} was calculated. θ was taken to be 1.6^o, where the GRAPES-3 angular resolution is $\sim 1^o$. The ϵ_{rej} calculated for each R_{core} discussed in section IV was used here. The observation time T was taken to be 1 year and effective time of observing CRAB to be 4 hours per day. The number of CR background events, the background events retained after applying the rejection criteria, the number of signal events (γ's) and the significance were calculated for the area for different R_{core} for the EMD using equation. 1 and the results are summarized in Table I.

The statistical significance for each R_{core} is shown in Fig.4 for different R_{core} for the PMD and the EMD. The data were plotted only for values of $R_{core} > 25$ meter where number of signal events is above 10. Decrease in

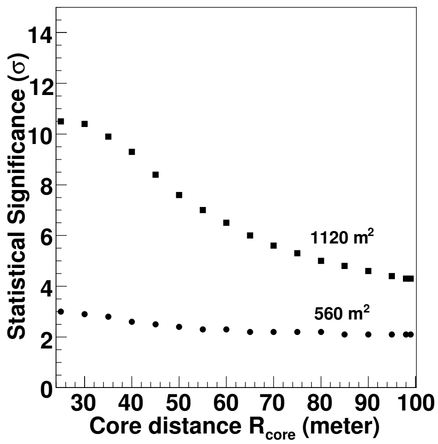

Fig. 4: Significance of Crab nebula as function of core distance with upper curve for the expanded muon detector and the lower curve for the present muon detector

significance is seen with increasing R_{core}. The results show that optimum value of R_{core} should be selected to get a maximum significance. With larger R_{core} though number of signal events increases, yet the significance decreases. which can be seen from the Table I. The EMD shows a higher significance than the PMD for same values of R_{core}. The optimum value of significance is $\sim$ 3 σ for the PMD and it is $\sim$ 10.5 σ for the EMD at R_{core} = 25 - 30 meters.

VI. Summary

The cosmic ray rejection efficiency as a function core distance was studied for the present and the expanded detector using the Monte Carlo simulations. Simulation results implies that a higher rejection efficiency can be achieved for a much farther core distance in the expanded detector. The significance from CRAB nebula was calculated and found to 3.5 times higher for the expanded detector. The selection of the core distance is very important to be get maximum efficiency. In the present simulation the efficiency of detecting γ-ray was taken to be 100$\%$ assuming γ-ray shower didn't contain any muon. However in reality the γ-ray showers have a small number of muons and these showers would get rejected as cosmic ray showers. This may affect the significance. However the relative significance may not change. A more realistic simulation is underway to take into account these effects.

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