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Characterizing the isotropic diffuse gamma-ray flux (10 – 300 TeV) by the GRAPES-3 experiment

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A diffuse gamma-ray emission at ~100 TeV can be expected as a result of the interactions of ultra-high-energy cosmic rays (UHECRs) with the cosmic microwave background (CMB) during their propagation. This radiation carries the information on the distribution of energetic sources and hence the cosmological evolution of the universe. The GRAPES-3 is an extensive air shower (EAS) array, located at Ooty in southern India. It consists of 400 plastic scintillators (each 1 m^2) and a large area (560 m^2) muon telescope. The muon telescope has the ability to differentiate the gamma-rays from charged cosmic rays through their muon content. We report on the study of isotropic diffuse gamma-ray flux from GRAPES-3 over 10 – 300 TeV.

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1. Introduction

The cosmic rays (CRs) spectrum spans over 12 orders of magnitude in energy (10^8 – 10^{20} eV) and nearly 32 orders of magnitude change in flux. Therefore, below 100 TeV CRs are detected directly by balloon and satellite experiments whereas above 100 TeV the measurements are carried out by large area ground-based extensive air shower (EAS) detector arrays.

Ultra-high-energy cosmic rays (UHECRs) are the particles of the highest energies, above 10^{18} eV, with an extreme low flux rate of $\leq$1 particle km^{-2} yr^{-1}. Therefore, even with large area EAS arrays of hundreds of km^2, it is enormously difficult to directly detect them. However, the UHECRs while propagating through the interstellar medium interacts with 2.7K cosmic microwave background (CMB) radiation via processes like pion photoproduction and Bethe-Heitler pair production [1]. The electromagnetic cascading results in a rapid loss of UHECRs energy often associated with Greisen-Zatsepin-Kuzmin (GZK) cutoff [2, 3]. The secondary electrons, positrons, and photons themselves interact with the CMB radiation and undergo further cascading which continues until the center of mass energy drops below the threshold, $\sim 10^{15}$ eV, of pair production. The photons that are the outcome of the cascading have energies, $E_\gamma \leq 100$ TeV with nearly diffuse and isotropic flux. These ultra-high-energy (UHE) γ-rays are within the reach of the current γ-ray detectors [1]. Therefore, by exploiting the indirect connection between UHECRs and UHE γ-rays, significant information can be extracted about the sites of the production and acceleration of these highest-energy particles.

In this contribution, we report upper limits on the isotropic gamma-ray flux over cosmic ray based on the observations by the GRAPES-3 experiment.

2. The GRAPES-3 experiment

The GRAPES-3 (**G**amma **R**ay **A**stronomy at **P**eV **E**nergie**S** – phase **3**) is an EAS array located at Ooty (11.4° N, 76.7° E, 2200 m a.s.l.), India. It consists of 400 plastic scintillators (each 1 m^2 in area) arranged in a hexagonal configuration covering a physical area of 25,000 m^2 with 8 m of inter-detector separation [4, 5]. The EAS array records about 3×10^6 events per day in the energy range 10^{12}–10^{16} eV.

The other major component is a large area tracking muon telescope (560 m^2) which comprises 3712 proportional counters (PRCs) housed in 4 stations [6]. Each station consists of 4 modules where in each module, the PRCs are arranged in 4 layers. Each layer consists of 58 PRCs of length 6 m having a square cross-sectional area of 0.1 m $\times$ 0.1 m. The alternating PRCs layers are orthogonally placed each separated by 15 cm thick concrete layer. The orthogonal configuration permits a two-dimensional reconstruction of muon tracks in two vertically orthogonal planes. Above each module, there is a mass overburden of 550 g.cm^{-2} in the form of concrete blocks stacked in an inverted pyramidal shape. The concrete absorber provides an energy threshold of secθ GeV for muons incident at zenith angle θ. A schematic view of the GRAPES-3 array is shown in Fig. 1.

3. Shower reconstruction

The GRAPES-3 experiment records the particle densities and the relative arrival times of secondaries for all the scintillator detectors. The two-level trigger system allows the elimination of

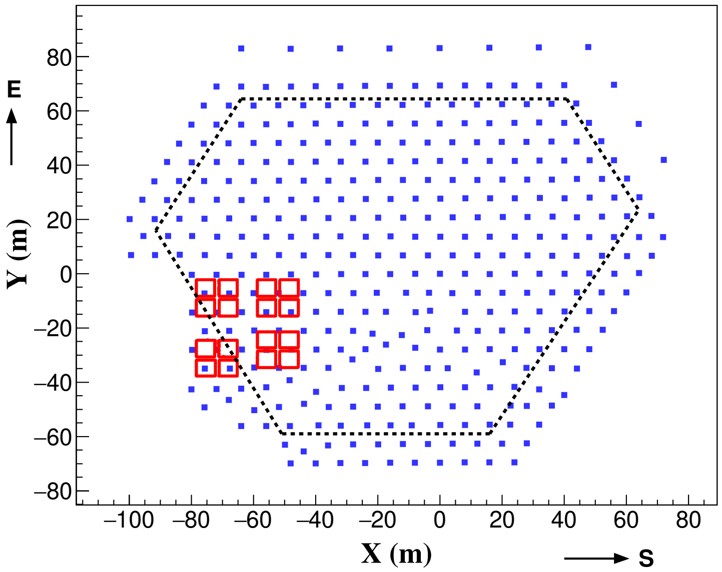


Figure 1: Schematic view of the GRAPES-3 EAS array. The small blue filled squares represent scintillator detectors and the 16 big red squares represent muon telescope modules. The dotted line represents the fiducial area used for this analysis.

small locally developed showers and also the large showers whose cores land outside the array. The relative arrival time is used to reconstruct the arrival direction of an EAS by fitting it with a plane EAS front. The shower parameters like core location, age, and shower size are obtained by fitting observed particle densities with a lateral density distribution function called Nishimura-Kamata-Greisen (NKG) formula [7, 8]:

$$\rho(r_i) = \frac{N_e}{2\pi r_M^2} \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)} \left(\frac{r_i}{r_M}\right)^{s-2} \left(1+\frac{r_i}{r_M}\right)^{s-4.5} \tag{1}$$

where N_e is the shower size, s is the shower age, r_i is the lateral distance of the i^{th} detector from the shower core, and r_M is the Moliére radius which is 103 m for the GRAPES-3.

After the reconstruction of shower parameters, a GEANT4 [9] simulation of the muon telescope is performed. Using the hit information of the PRCs, the muon track is identified with any three-layer coincidence out of four. The muon number is counted from the observed muon tracks in the detector for those showers whose direction matches the air shower direction. The muon tracks counting rate unrelated to air shower triggers is 3000 Hz per module. Therefore, the average number of muons due to chance coincidence is estimated to be very small, about 0.07 per event [10].

4. Analysis

4.1 Data Selection

The data recorded between January 01, 2014 to December 31, 2014 are used for this analysis. To ensure the quality of the data, events are selected which passes the following quality cuts:

1. The reconstructed cores must lie inside the fiducial area of about $14,500\ m^2$.
2. The reconstructed age parameter (s) is restricted to $0.12 \leq s \leq 1.8$.
3. Zenith angle is restricted to less than 25°.

4.2 Gamma-ray simulation

A detailed Monte-Carlo simulation of the air shower development with primary gamma-rays is carried out with CORSIKA (version 7.4001) [11] to obtain the muon number distribution and estimate the median γ-ray energy. The hadronic interaction models used are SIBYLL 2.1 [12] and FLUKA 2011 [13], for high and low energy, respectively. The showers are generated in the energy range 5 TeV to 10 PeV for zenith angle less than 60° with a differential energy spectrum of $E^{-2.7}$. The CORSIKA simulated showers are then passed through the GRAPES-3 analysis framework developed in-house to generate the triggers and record the GEANT4 response of each scintillator detector. The shower cores are thrown randomly with each core reused 10 times in radial bins of 5 m (0 - 5 m, 5 - 10 m, ..., 115 - 120 m) from the center of the muon telescope. The angle and the shower parameters are reconstructed using the time of flight (TOF) and particle density information of the secondaries. The simulation of the muon telescope is performed by using the GEANT4 package.

4.3 Gamma hadron discrimination

The gamma-ray induced showers have notably less muon content as compared to hadronic showers. Therefore, based on the number of muon content in each triggered shower, the charged cosmic ray background can be efficiently rejected, thereby, enabling the study of multi-TeV γ-rays. Motivated by the above fact, the selection of gamma-like (muon-poor) showers is performed by considering showers with zero muon content only.

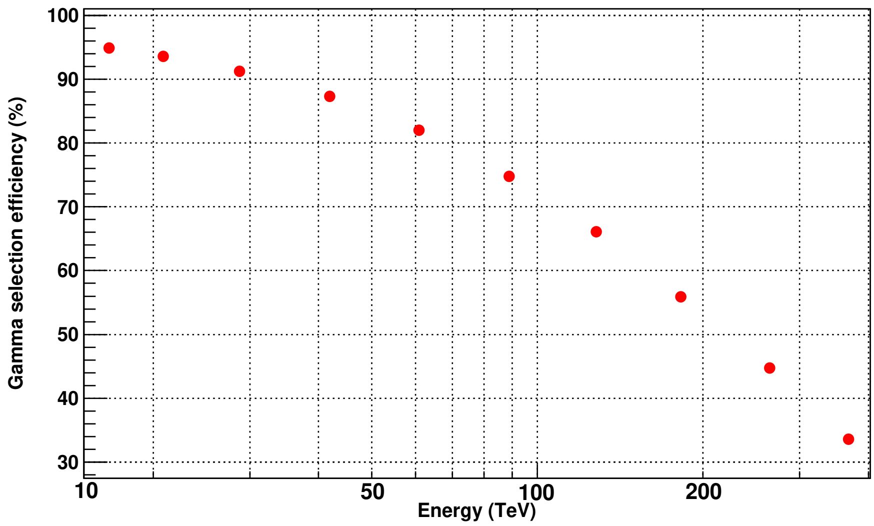
From the gamma-ray simulation, selection efficiency, ϵ_γ, is calculated by taking the ratio of muon-poor showers to the total number of incident showers for each radial bin of 5 m from the center of the muon telescope and size bin of logarithmic interval of 0.2. Similarly, the cosmic ray rejection efficiency is calculated from the one-year data by subtracting the muon-poor showers from the total incident showers and then taking the ratio of remaining showers with the total incident showers for each radial and size bin.

For this analysis, we considered a radial distance of up to 30 m from the center of the muon telescope. In Fig. 2, variation of γ-ray selection and cosmic ray rejection efficiency with energy is plotted for the selected radial distance.

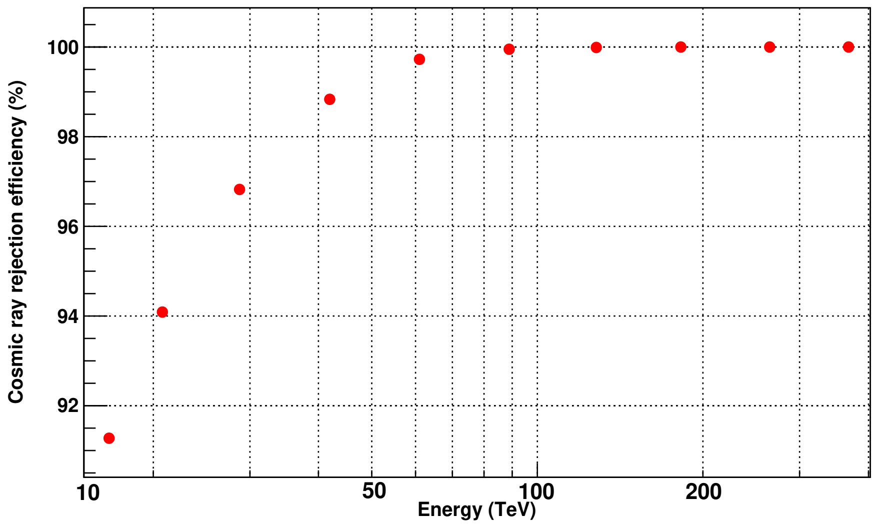
5. Upper limit of I_γ / I_{CR}

The upper limit on the ratio of gamma-ray over cosmic ray integral flux is given by [10]:

$$\frac{I_\gamma}{I_{CR}} \leq \frac{N^{\mu=0}_{90\%\,C.L.}}{N_{tot}} \frac{1}{\epsilon_\gamma} \frac{1}{1 - n_{chance}} \tag{2}$$



(a) Gamma-ray selection efficiency



(b) Cosmic ray rejection efficiency

Figure 2: Variation of γ-ray selection (top) and cosmic ray rejection efficiency (bottom) with energy for a radial distance of 30 m from the center of the muon telescope.

where $N^{\mu=0}_{90\% C.L.}$ is the 90% confidence limit on the number of muon-poor showers assuming Poisson distribution [14, 15], N_{tot} is the total number of showers, ϵ_γ is the selection efficiency and n_{chance} is the average number of muons due to chance coincidence.

The values of N_{90}, N_{tot}, ϵ_γ, E_γ and I_γ/I_{CR} are listed in Table 1 for different threshold values of $logN_e$ and at a radial distance of 30 m from the center of the muon telescope. The result is plotted in Fig. 3 and compared with the upper limits given by other groups.

$logN_e$	N_{90}	N_{tot}	ϵ_γ	E_γ (TeV)	I_γ/I_{CR} (90%$C.L.$)
>3.2	3751583	42951530	0.95	16.62	$< 9.89 \times 10^{-2}$
>3.4	1839029	31002350	0.94	20.87	$< 6.81 \times 10^{-2}$
>3.6	606500	19040380	0.91	28.71	$< 3.75 \times 10^{-2}$
>3.8	120176	10207810	0.87	41.91	$< 1.45 \times 10^{-2}$
>4.0	14512	5057460	0.82	60.99	$< 3.77 \times 10^{-3}$
>4.2	1318	2425239	0.75	88.83	$< 7.81 \times 10^{-4}$
>4.4	136	1161471	0.66	128.00	$< 1.91 \times 10^{-4}$
>4.6	18	555111	0.56	182.26	$< 6.24 \times 10^{-5}$
>4.8	5	259936	0.45	264.60	$< 4.62 \times 10^{-5}$
>5.0	4	112144	0.34	368.04	$< 1.14 \times 10^{-4}$

Table 1: 90% C.L. upper limit on the ratio of γ-ray over cosmic ray integral flux at different threshold values of $logN_e$ and a radial distance of 30 m from the center of the muon telescope.

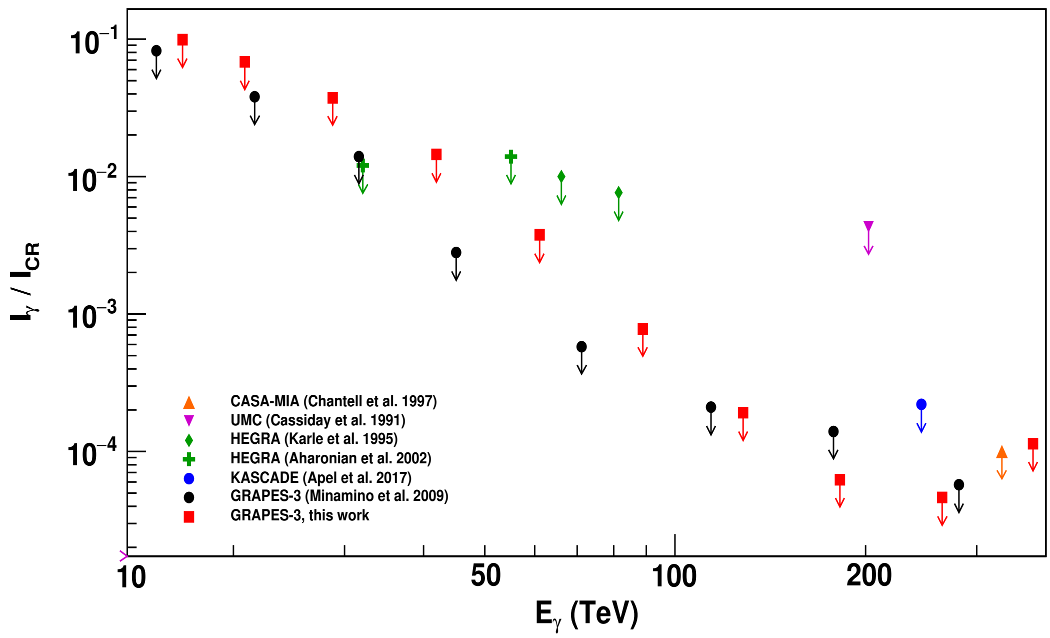


Figure 3: Upper limit measurements of the fraction of isotropic γ-rays relative to cosmic rays. The points with arrows represent upper limits from the CASA-MIA [16], UMC [17], HEGRA [18, 19], KASCADE [20], GRAPES-3 [10] and this work, as indicated in the legend.

6. Summary

Using the data sets measured by the GRAPES-3 experiment between January 2014 to December 2014, we place a 90% C.L. upper limit on the fraction of gamma-ray to cosmic ray flux at energies between 10 – 300 TeV. The best upper limits are obtained: $I_\gamma/I_{CR} \leq 6.24 \times 10^{-5}$ for 182.3 TeV and $I_\gamma/I_{CR} \leq 4.62 \times 10^{-5}$ for 264.6 TeV.

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