PROCEEDINGS OF SCIENCE

Highlights from the GRAPES-3 Experiment on Galactic Cosmic Ray Measurements

P.K. Mohanty,[a,*] **M. Chakraborty**[a,b] **and F. Varsi**[c] **for the GRAPES-3 collaboration**

[a] *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India.*

[b] *IRFU, CEA, Université Paris-Saclay, Bât 141, 91191 Gif-sur-Yvette, France (current affiliation)*

[c] *Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany*

E-mail: pkm@tifr.res.in

The GRAPES-3 experiment, located in Ooty, India (11.0°N, 76.7°E, 2200 m a.s.l.) comprises a dense array of 400 plastic scintillator detectors and a 560 m^2 area muon telescope to measure electromagnetic and muonic components of cosmic ray showers. The experiment could successfully measure the cosmic ray proton spectrum in the energy range of 50 TeV - 1.3 PeV, providing an overlap with direct measurements. The relative proton fraction was determined using muon multiplicity distributions. A spectral hardening was observed above 165 TeV, challenging the simple power-law description extending to the knee energy. Additionally, we have observed both small and large scale cosmic ray anisotropies. We observed two significant small-scale anisotropic features at a median energy of 16 TeV using the time-scrambling method, consistent with results from the HAWC and ARGO-YBJ experiments. However, for the observation of large-scale anisotropy, we used an iterative maximum-likelihood approach for retrieving attenuated signals which occurs due to the limited instantaneous field of view for low latitude location of GRAPES-3. We successfully observed large scale anisotropy with a statistical significance of six standard deviations and the results are consistent with other experiments both in amplitude and phase. We have added another muon telescope to the experiment. The new muon telescope, covering an area of 570 m^2 is nearing its completion, with 75% of its modules already operational. The two muon telescopes combined will provide two times larger detection area which could result in an enhanced sensitivity particularly for the detection of PeV gamma-ray sources and mass composition measurements below 100 TeV.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

[*] Speaker

PoS(ICRC2025)335

1. The GRAPES-3 experiment

GRAPES-3 (abbreviation for Gamma-ray Astronomy at PeV EnergieS Phase-3) is a major cosmic ray observatory, located in Ooty, India (11.4°N, 76.7°E and 2200 m a.s.l.) [1, 2] to study galactic cosmic ray phenomena in TeV-PeV energy region. It consists of two main detector systems as shown in the schematic in Figure 1; (1) an array of 400 closely spaced plastic scintillator detectors of 1 m^2 area each spread over an area of 25,000 m^2, and (2) a tracking muon detector consisting of 16 modules of 35 m^2 area each.

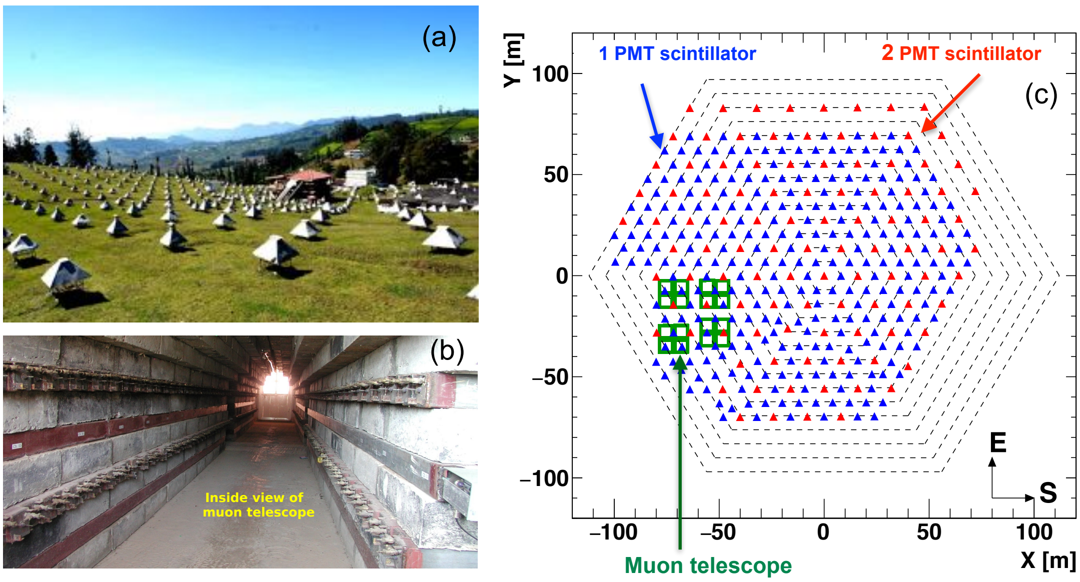

Figure 1: (a) A view of the GRAPES-3 experiment with the scintillator detectors seen as white conical structure, (b) inside view of one of the muon detector station, and (c) a schematic of the array.

The scintillator detectors record the shower particles which are composed of mostly electron components. The scintillator array generates the shower trigger when a minimum of 10 detectors receive a signal above 0.5 particles equivalent of the minimum ionizing muon. The current trigger rate of the array is ~40 per second. The charge from the photomultiplier tube of each scintillator detector is digitized through an analog-to-digital converter which is used to estimate the particle density whereas the arrival time of the signal is digitized by time-to-digital converter which is used to estimate the direction of the shower. The lateral distribution of the particle densities is used to estimate the location of the core, the size of the shower, and the age parameter [3].

Each module of the muon telescope is designed with four layers of gas-filled proportional counters (PRCs), made of 6 m square iron tubes with a cross section of 0.1m×0.1m [4]. The orthogonal arrangement of the PRCs helps to track muons, allowing us to determine their arrival direction. A concrete shielding of 550 g cm^{-2} provides a threshold of 1 GeV for vertically incident muons. Muons are recorded for individual showers following the arrival of the shower trigger generated by the scintillator array. The muon component along with the other shower parameters is used to measure the mass composition of primary cosmic rays. This is also used for rejection of the cosmic ray background for gamma-ray studies. With an independent data acquisition system, the individual muon is triggered by taking the coincidence of signals from four layers of the PRCs. This provides measurement of muon flux at a rate of ~3000 per second per module and ~ 50000 per second from 16 modules. The direction of muons are determined in 169 bins with an average angular resolution of 4°. This data is used to study solar and thunderstorm phenomena.

2. Measurements of Cosmic Ray Proton Spectrum

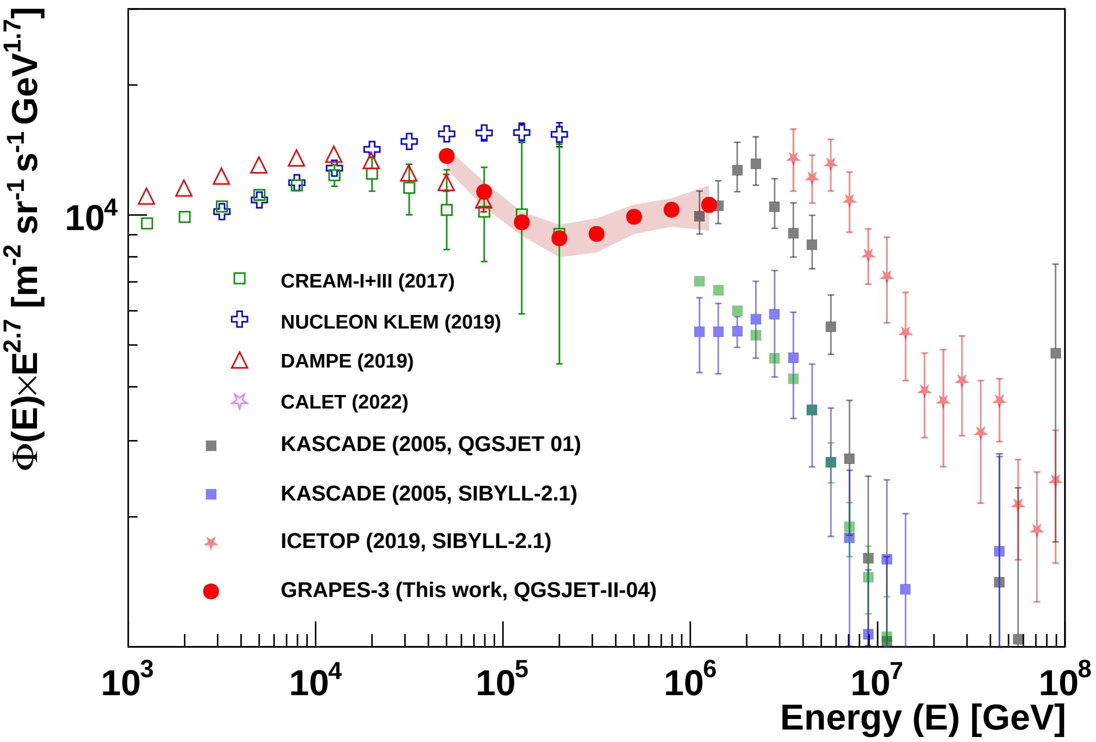

Figure 2: Cosmic ray proton spectrum measured by the GRAPES-3 experiment from 50 TeV to 1.3 PeV which is presented along with the results from space-based and ground-based experiments. For GRAPES-3 data points, the statistical errors are smaller than the size of the symbols while the total errors (statistical + systematic) are presented by the shaded band.

We measured cosmic ray proton spectrum from 50 TeV to 1.3 PeV using data recorded by the GRAPES-3 experiment from 1 January 2014 to 26 October 2015. The details of the analysis are provided in [6]. The analysis used a total of 1.75×10^9 shower events that were recorded over a live time of approximately 460 days. Various selection criteria and cuts resulted in 7.81×10^6 events for the final analysis. Showers of a size greater than 10^4 were considered in which the trigger efficiency is greater than 90%. This corresponds to a primary proton energy of 50 TeV and iron of 80 TeV. Showers with a zenith angle of less than 18° were used.

Muon multiplicity distribution is a sensitive parameter for the mass composition, which was used for this analysis. We compared the observed muon multiplicity distributions with simulations assuming five primary mass groups, namely, proton (H), helium (He), nitrogen (N), aluminum (Al) and iron (Fe). Here, N represents the C-N-O group, Al represents the Mg-Al-Si group, and Fe represents the Mn-Fe-Co group. The relative contribution of each mass group that represents the composition was obtained using an unfolding technique with particular focus on protons.

The proton size spectrum was derived from the data size spectrum using the composition weights, and the proton energy spectrum was obtained via unfolding. These results are presented in Figure 2, alongside data from other direct and indirect experiments. Statistical errors are smaller than the data point markers. The total error represented by the shaded band is dominated by the systematic error (please refer to [6] for more details). The proton spectrum agrees well with direct measurements at lower energies and with the KASCADE spectrum obtained using the pre-LHC QGSJet01 hadronic model. A hardening of the spectrum is observed at 164±55 TeV, with spectral indices of -3.1±0.19 and -2.59±0.09 before and after the break energy, respectively. These results indicate that the proton spectrum below the knee energy cannot be described by a simple single power-law model.

3. Measurements of Cosmic Ray Anisotropy

Cosmic ray anisotropy is one of the key probes for understanding sources, acceleration, and propagation of cosmic rays. GRAPES-3 experiment has a geographical advantage in studying cosmic ray anisotropy as it has an overlapping field of view with experiments in the northern and southern hemisphere. Due to the tiny amplitude of anisotropy (order of 10^{-4} - 10^{-3}), high statistics data are required. GRAPES-3 records over 10^9 shower events per year, enabling it for ansitropy measurements in TeV energies.

We measured small-scale cosmic ray anisotropy using shower events recorded by the GRAPES-3 scintillator array between 1 January 2014 and 31 December 2016, comprising 3.7×10^9 events. Detailed analysis and results are provided in [7]. The time scrambling method was used for the analysis. Two statistically significant excess regions with angular scales less than 60° have been observed with amplitude of $(6.5\pm1.3)\times10^{-4}$ and $(4.9\pm1.4)\times10^{-4}$ and significance of 6.8σ and 4.7σ, respectively. These observations are consistent with a few other air shower experiments. The structures have been confirmed to be of cosmic ray origin utilizing the muon detection feature of the GRAPES-3 experiment.

Two statistically significant structures, labeled A and B, were observed, as shown in Figure 3. The amplitudes of regions A and B were measured to be $(6.5\pm1.3)\times10^{-4}$ and $(4.9\pm1.4)\times10^{-4}$, respectively, with statistical significances of 6.8σ and 4.7σ. Region A is observed within a right ascension of $\sim 50^\circ$ to 90° and a declination of $\sim -15^\circ$ to 30°. Region B is an elongated structure observed within $\sim 110^\circ$ to 140° of the right ascension and almost throughout the full declination range. These results are consistent with observations from the Milagro, HAWC, and ARGO-YBJ experiments.

The method used to obtain the small-scale anisotropy for GRAPES-3 was not effective in extracting the large-scale anisotropy. This is because mid-latitude detectors such as GRAPES-3 and HAWC have limited instantaneous sky coverage, resulting in the attenuation of signal amplitudes.

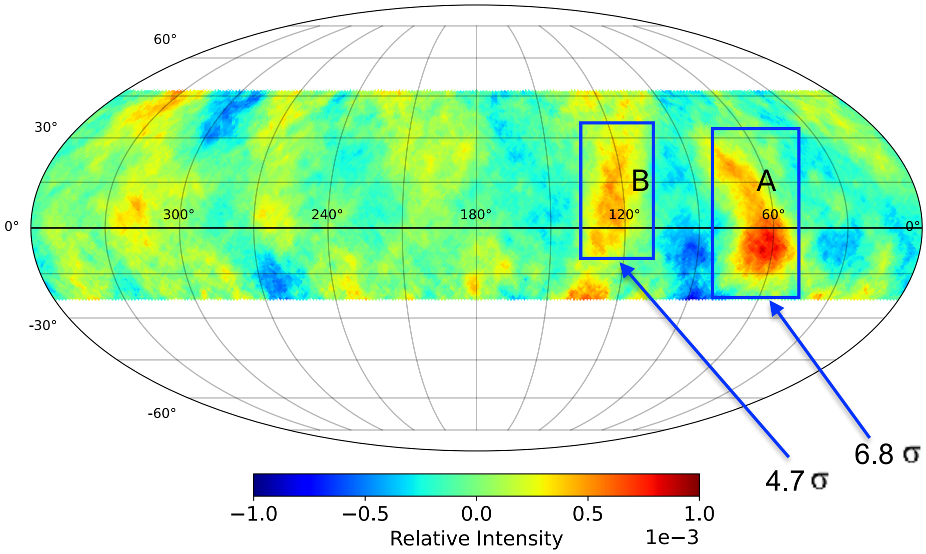

Figure 3: Small-scale cosmic ray anisotropy observed by the GRAPES-3 experiment is shown including the relative intensity and significance maps. The two structures denoted by A and B are observed with significance of 6.8σ and 4.7σ, respectively.

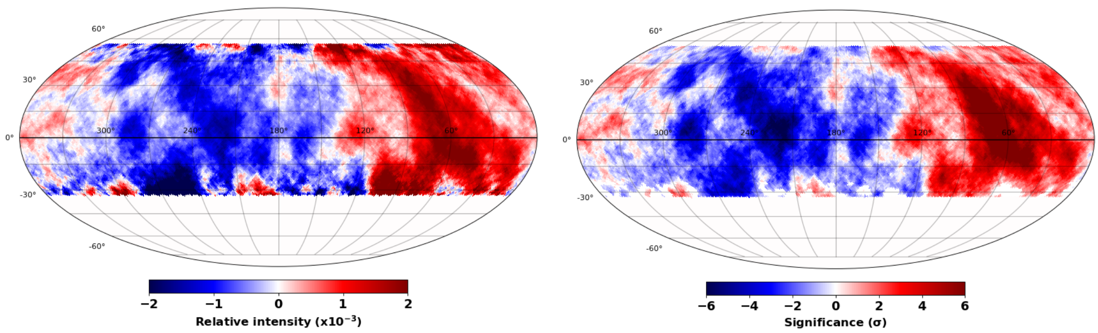

Figure 4: Relative intensity and pixel-wise significance of all harmonics observed with a top-hat smoothing radius of 10° at the end of 40 iterations using iterative likelihood method [8]

To overcome this problem, we applied an iterative likelihood method developed in [8]. A year of data recorded by the GRAPES-3 experiment (between January 1, 2013, and December 31, 2013) was used for the analysis to demonstrate the observation of large-scale anisotropy. The details of the analysis method are described elsewhere [9]. The amplitude of the anisotropy has improved with higher iterations, while there is no significant change after 40 iterations. The results are shown in Figure 5.

A broad excess is observed between 30° and 130° in the right ascension, while a wide deficit spans 130° and 300°. The maximum excess reaches 2×10^{-3}, with a maximum significance of 6σ. These results cover the declination range −28.6° to 51.4°, that is, ±40° from the GRAPES-3 zenith at 11.4°. By removing higher harmonics, we obtained dipolar anisotropy with an amplitude of $(1.12 \pm 0.05)\times10^{-3}$ with a phase of approximately 58°. The results are comparable with those of other experiments.

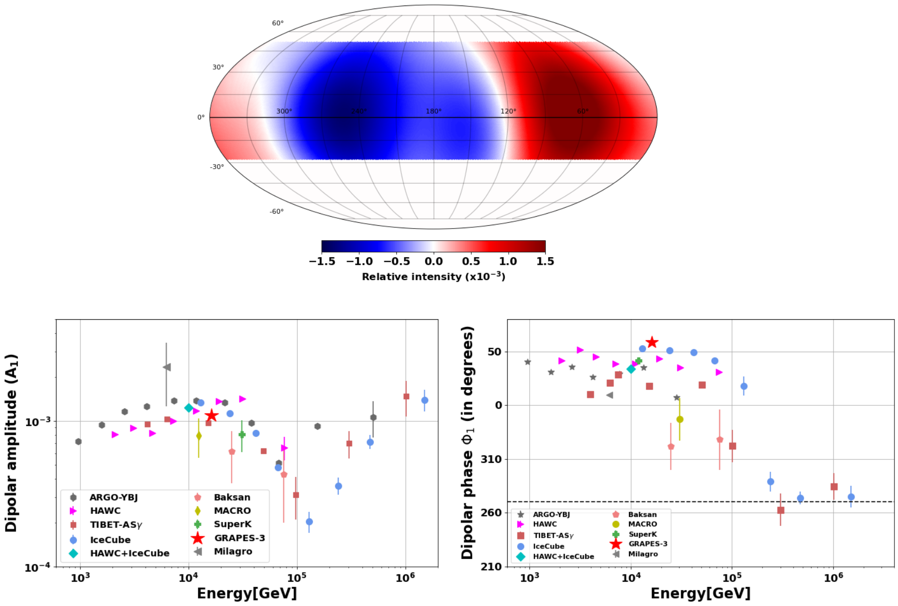

Figure 5: Top figure shows the large-scale anisotropy (l ≤ 3) was extracted from the relative intensity map obtained at the end of 40 iterations. The bottom figure represents the amplitude and phase of the anisotropy from the GRAPES-3 experiment compared with others [9]

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4. Expansion of the Muon Telescope

To enhance the sensitivity of the GRAPES-3 experiment, particularly in detecting PeV gamma ray sources and obtaining a better mass composition of cosmic rays below 100 TeV, a second muon telescope similar to the area of the existing muon telescope has been built, providing a total detection area of 1130 m^2. It utilizes proportional counters (PRCs) (6m×0.1m×0.1m) as its basic detector units, which were fabricated in the GRAPES-3 laboratory. New front-end electronics with low-noise amplifier and discriminator were also developed in house that replaced the four-decade-old electronics [10]. Further signal processing and data acquisition electronics were developed in-house based on the Field Programmable Gate Array (FPGA) [11]. The second muon telescope also consists of 16 modules similar to the first muon telescope. However, all modules are housed under a single roof. The target is to place a concrete absorber of 550 g cm^{-2} to provide a threshold energy of 1 GeV for vertically incident muons by shielding the electromagnetic components. Currently, only 50% absorbers are placed in providing a threshold of 0.5 GeV. Of the 16 modules, 12 modules (75%) have been fully operational and have been recoding the data for the past several months. The commissioning of the electronics of the remaining four modules is in progress. Some pictures of the new telescope have been provided in Figure 6.

Figure 6: New muon telescope, top view (left) and inside view (right)

5. Acknowledgments

The authors thank D.B. Arjunan, A.S. Bosco, V. Jeyakumar, S. Kingston, N.K. Lokre, K. Manjunath, S. Murugapandian, S. Pandurangan, B. Rajesh, R. Ravi, V. Santhoshkumar, S. Sathyaraj, M.S. Shareef, C. Shobana, R. Sureshkumar for their role in the efficient running of the experiment. The support of the Department of Atomic Energy, Government of India, is acknowledged under Project Identification No. RTI4002 is acknowledged.

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