PROCEEDINGS OF SCIENCE

Recent results from the GRAPES-3 experiment

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The GRAPES-3 experiment located in Ooty, India at an altitude of 2200 m is operating with a dense array of scintillator detectors and a large area muon telescope to sample the electromagnetic and muonic components in the cosmic ray showers respectively. It records about a billion shower events per year. Here we discuss the GRAPES-3' s recent measurements of cosmic ray proton energy spectrum below the Knee. We provide an overview of the cosmic ray small anisotropy results at TeV energies with two distinct structures which are also consistent with the observation of other air shower arrays. The status of the upgrade of the GRAPES-3 experiment is discussed.

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[*] Speaker

1. The GRAPES-3 experiment

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

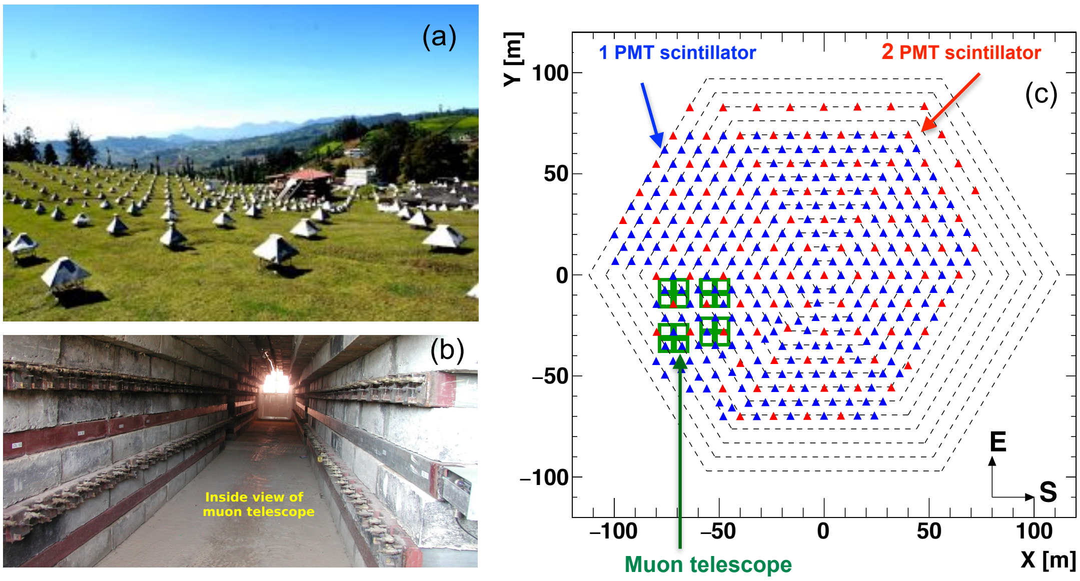

Figure 1: (a) A view of the GRAPES-3 experiment with the scintillator detectors seen as white conical structure, (b) inside view of one of the muon detector station, and (c) a schematic of the array.

The scintillator detectors record the shower particles which are composed of mostly electron components. The scintillator array generates the shower trigger when a minimum 10 detectors receives signal above 0.5 particle equivalent. The current trigger rate of the array is ~40 per second. The charge from the photomultiplier tube of each scintillator detector is digitized through 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 core location, shower size and age parameter [4].

Each module of the muon telescope is designed with four layers of proportional counters, made of square iron tubes of length 6 m and cross section of 0.1m×0.1m [3]. The orthogonal arrangement of the PRCs allows the tracking of muons. 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 shower trigger generated by the scintillator array. The muon component along with the other shower parameters are used to measure the mass composition of primary cosmic rays. It is also used for rejection of cosmic ray background for gamma ray studies. With an independent data acquisition system, individual muon is triggered by taking coincidence of signals from four layers of the PRCs. This provides the measurement of the 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. Performances of the scintillator array

The scintillator performances were evaluated through simulation by generating showers with CORSIKA package. The response of detectors were folded using GEANT4 simulation. Due to the mid-altitude location and close seperation (8 m) of the detectors, the array enables to trigger showers as low as 1 TeV energy. The median energy of triggered showers is 15 TeV. The trigger efficiency obtained from simulations for five different primary masses is shown in Figure 2a. The array achieves more than 90% trigger efficiency for proton showers at energy ~40 TeV for zenith angle below 18°. Same trigger efficiency is achieved for iron initiated showers at 80 TeV energy.

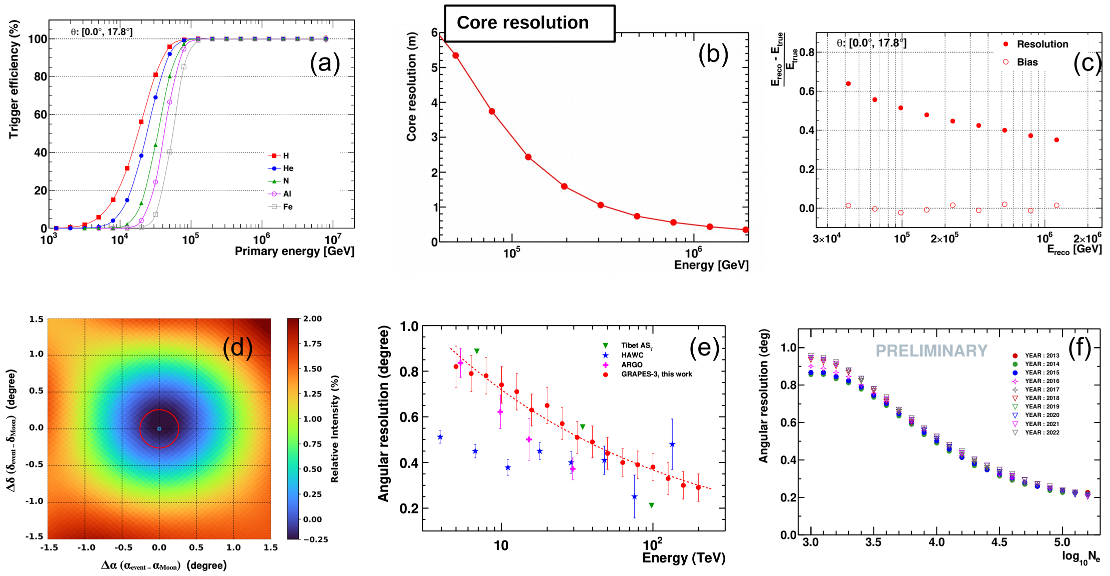

Figure 2: Performances of the scintillator array; (a) trigger efficiency based on the simulation for five different cosmic ray primaries, (b) the core resolution for proton primaries , (c) the energy resolution and bias for proton primary, (d) Moon shadow observation based on data from 2014 to 2016, (e) angular resoultion based on Moon shadow which are compared with other experiments, and (f) angular resolution based on left-right array division method to check the stability of the array.

The core resolution for proton showers is shown in Figure 2b. It can be seen that the core resolution is 6 m at 40 TeV energy which improves to 2 m at 100 TeV and ~0.5 m at 1 PeV energy.

The energy resolution is obtained by comparing the true energy with the reconstructed energy and the energy bias is defined as the offset of the energy. Energy resolution and bias for proton primary is shown in Figure 2c. The energy resolution is about 65% at 40 TeV which improves 35% at 1 PeV. The energy bias is consistent with zero.

The angular resolution of the array has been improved significantly after the correction of shower front curvature based on size and age [4]. It was validated using observation of Moonshadow [5]. The angular resolution is 0.85° for all showers which improves to 0.35° at 100 TeV. The results of Moonshadow observation is shown in Figure 2d which is compared with other experiments in Figure 2e. The stability of the angular resolution from 2013 to 2022 is shown in Figure 2f. Slightly poor angular resolution after 2016 in the smaller shower size is due to the changing of the trigger area that resulted in recording of more low energy showers.

3. Results

3.1 Cosmic ray proton spectrum

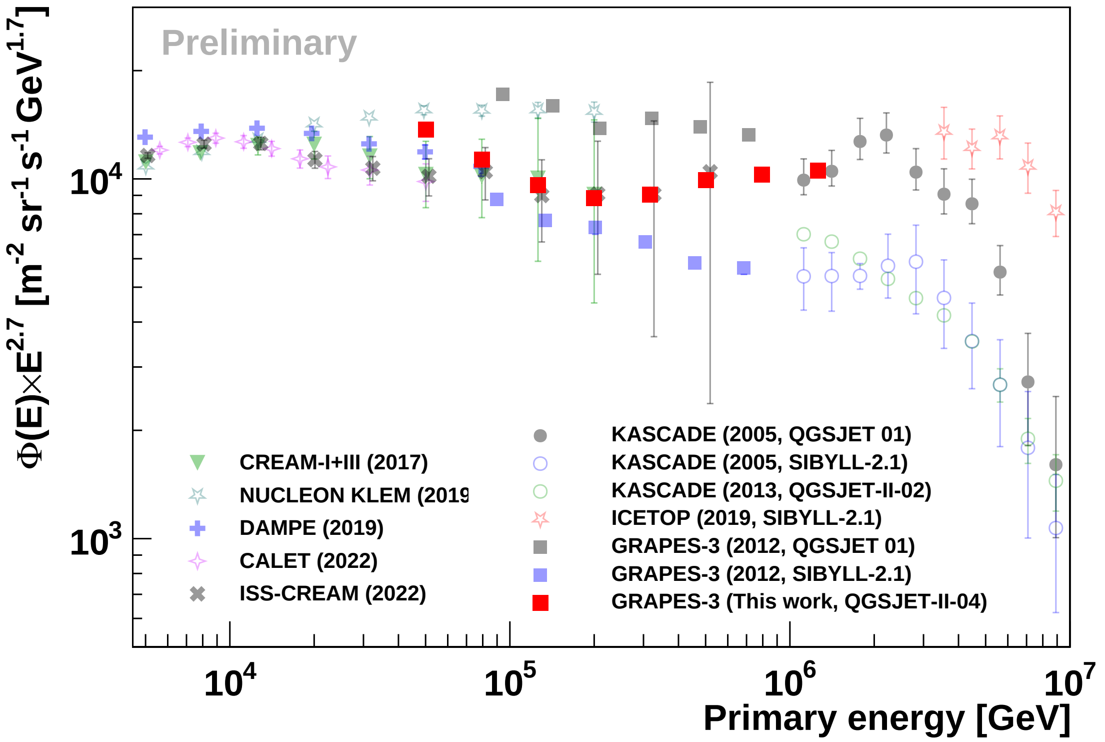

Figure 3: Cosmic ray proton spectrum measured by the GRAPES-3 experiment from 40 TeV to 1.3 PeV which is presented along with the results from direct and indirect experiments.

We measured the proton spectrum from 40 TeV to 1.3 PeV. The details of the analysis are provided in [6]. Data recorded from 1 January 2014 to 26 October 2015 with a total of 1.75×10^9 shower events was used for this analysis for a live time period of ~460 days. The number of events after various selections and cuts is 7.81×10^6. To ensure trigger efficiency more than 90%, shower size $>10^4$ was used for this analysis. The energy of the proton primary at this shower size is 40 TeV and for iron primary, it is 80 TeV. The zenith angle was selected less than 18°. The observed muon multiplicity distributions were compared with that of simulations of five assumed primary masses such proton (H), Helium (He), Nitrogen (N), Aluminum (Al) and Iron (Fe) whereas N represents for (C,N,O) group, Al represents (Mg,Al,Si), and Fe represents for (Mn,Fe,Co). The relative composition of each mass group was obtained using unfolding technique. Proton was studied in more detail. Proton size spectrum was obtained from the data size spectrum using the weights of its composition. The proton energy spectrum was obtained using unfolding technique and the results are presented in Figure 3 along with the results from various direct and indirect experiments. The statistical errors are smaller than size of the data points. A good agreement is seen with direct measurements at low energies whereas it agrees with KASCADE spectrum obtained with pre-LHC QGSJet01 hadronic model. The spectrum shows a hardening at 165±53 TeV with spectral indices of -3.1±0.18 and -2.59±0.09 before and after the break point. The results are inconsistent with a single power law description of the proton spectrum below the Knee energy.

3.2 Cosmic ray anisotropy

We measured the cosmic ray anisotropy using the shower events recorded by the scintillator array from 1 January 2014 to 31st December 2016, comprising 3.7×10^9 events. The details of the analysis can be found in [7]. Time scrambling method was used for the analysis. We observed two statistically significant structures namely A and B as shown in Figure 4. The amplitudes of region A and region B are $(6.5\pm1.3)\times10^{-4}$ and $(4.9\pm1.4)\times10^{-4}$, respectively. The statistical significance of A and B are 6.8σ and 4.7σ, respectively. The results are consistent with the observations of Milagro, HAWC and ARGO-YBJ experiment.

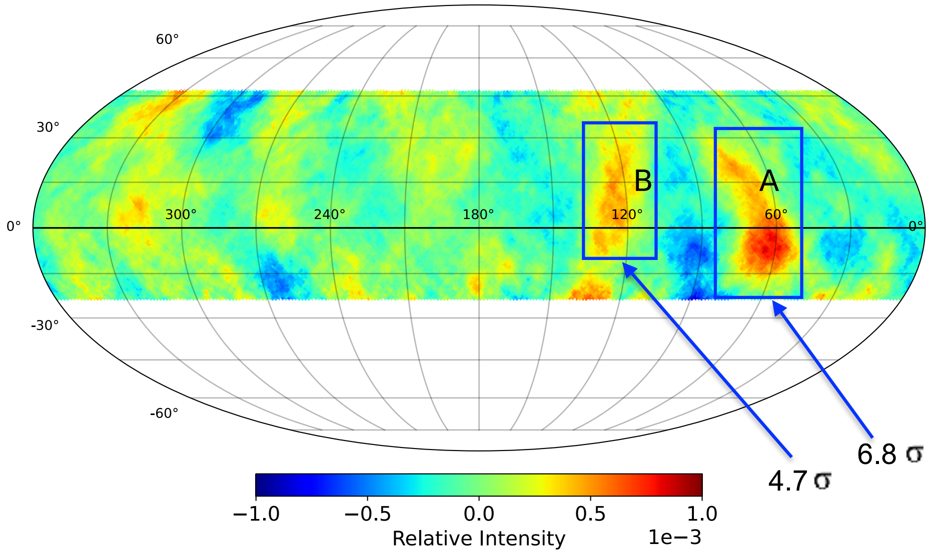

Figure 4: Cosmic ray anisotropy observed by the GRAPES-3 experiment.

4. Expansion of the GRAPES-3 muon telescope

The muon telescope of the GRAPES-3 experiment is a key detector for measuring cosmic ray mass composition, multi-TeV gamma ray astronomy, and solar and atmospheric physics. Upgrade to double its detection area is under progress. The expanded muon telescope (from 560 m^2 to 1130 m^2) will provide the same level of sensitivity for gamma ray detection in one year as the existing telescope could do in ten years. Additionally, this new telescope will help to produce more reliable mass separation of cosmic rays in the low energy range below 100 TeV. The telescope utilizes proportional counters (PRCs) (6m×0.1m×0.1m) as its basic detector units. In order to obtain the nearly 4000 PRCs needed for the updated telescope, a three year research and development period was undertaken to fabricate the necessary PRCs from rusted iron tubes from Kolar Gold Field underground experiments. The required number of PRCs have been successfully fabricated and installed in the field. The civil work including 50% of absorber in form of concrete is complete. New front electronics has been developed which will replace the four decade old electronics [8]. FPGA based DAQ electronics have been developed which have significantly minimise the dead time of the system [9]. One of the 16 modules was made operational in February 2023. Some pictures of the new muon telescope is shown in Figure 5.

Figure 5: (a) Test bench for PRC vacuum creation and gas filling, (b) testing of PRC performances, (c) 16 modules of the new muon telescope, and (d) operation of the first module of the new muon telescope.

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References

[1] S. K. Gupta et al., *GRAPES-3—A high-density air shower array for studies on the structure in the cosmic-ray energy spectrum near the knee*, *Nucl. Instrum. Meth. Phys. Res. A* **540** (2005) 311.

[2] P. K. Mohanty et al., *Measurement of some EAS properties using new scintillator detectors developed for the GRAPES-3 experiment*, *Astropart. Phys.* **31** (2009) 24.

[3] Y. Hayashi et al., *A large area muon tracking detector for ultra-high energy cosmic ray astrophysics—the GRAPES-3 experiment*, *Nucl. Instrum. Meth. Phys. Res. A* **545** (2005) 643.

[4] V.B. Jhansi et al., *T*he angular resolution of GRAPES-3 EAS array after improved timing and shower front curvature correction based on age and size, *J. Cosmol. Astropart. Phys.***07**, 024 (2020).

[5] D. Pattanaik et al., *V*alidating the improved angular resolution of the GRAPES-3 air shower array by observing the Moon shadow in cosmic rays, *Phys. Rev. D***106**, 022009 (2022).

[6] F. Varsi et al., *C*osmic ray proton energy spectrum below the Knee observed by the GRAPES-3 experiment, *Proceedings of 38th International Cosmic Ray Conference, PoS(ICRC2023)* **444** (2023)0520.

[7] M. Chakraborty et al., *S*mall-scale anisotropy in the cosmic ray flux observed by GRAPES-3 at TeV energies, *Proceedings of 38th International Cosmic Ray Conference, PoS(ICRC2023)* **444** (2023)0513.

[8] K. Ramesh et al., *H*igh-Performance and Low-Noise Front-End Electronics for GRAPES-3 Muon Telescope, *Experimental Astronomy*, **56** (2023)31-37.

[9] A. Jain et al., *A*n Advanced Triggerless Data Acquisition System for the GRAPES-3 Muon Detector, *Proceedings of 37th International Cosmic Ray Conference, PoS(ICRC2021)* **395** (2023)257.