Gamma ray astronomy at PeV energieS

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The GRAPES-3 (Gamma Ray Astronomy at PeV EnergieS Phase 3) experiment is a collaboration project amongst universities and institutes in our country along with Japan. The experiment employs a high density array of plastic scintillation detectors and a large area tracking muon telescope. The scintillation detectors detect the electrons in an air shower for getting information on the shower, particularly for generating trigger, determining arrival direction and estimating the energy of the primary particle. The muon telescope detects and measures the muon component in the extensive air shower (EAS). The muon telescope is an effective tool, in the study of the nuclear composition of primary cosmic rays. The tracking muon telescope has also proved to be an invaluable tool in the studies of the solar flares, coronal mass ejections and the subsequent Forbush decrease events observed at the Earth. The collaboration is being expanded with addition of several major facilities like Cherenkov telescope, low frequency dipole array for the measurement of shower energy, addition of several modules of muon telescopes to cover a large area and a neutron monitor. In this article we briefly describe the experiment from its beginning.

The term 'cosmic rays' refers to highly energetic charged particles[1] constantly impinging onto the earth's atmosphere from outer space. These particles are commonly referred to as primary particles or simply primaries. Cosmic radiation was discovered in 1912 by measuring their discharge effects in electroscopes during balloon flights[2]. They are composed of distinct types of charged particles like protons, fully ionized atomic nuclei and electrons. Their energies cover 11 orders of magnitude from 10^9 to 10^{20} eV.

Although cosmic rays were discovered almost a century ago, they are still subject to intensive studies even today. Many important questions could not be answered so far, like the type and location of their sources, the underlying acceleration mechanisms or their exact chemical composition at energies above 100 TeV. Satellites and balloons carrying particle detectors are used to study cosmic radiation of energy below 100 TeV. At higher energies ~10^{14} eV, ground based arrays of particle detectors like KASCADE Grande[3], AKENO[4], GRAPES[5] are used to study the primary cosmic radiation indirectly by investigating the properties of extensive air showers[6], which are initiated by the interaction of the primaries with air nuclei.

The shower products can be classified into four categories: the electron component (electron, positron and gamma rays), the muon component (positive and negative muon), the hadrons component (pions, kaons, nucleons, etc.), and Cerenkov photons. Amongst these components, it is well established that the muon component has the highest sensitivity in distinguishing between the various primary nuclei. Earlier experiments studied the muon component associated with EAS (Extensive Air Shower) having relatively small area detectors, usually a few tens of m^2 for lower energies observed on the ground and only a few m^2 for higher energies deeper underground. Recently several groups like EASTOP[7], KASCADE[8], GRAPES-2 (ref. 9) and GRAPES-3 (ref. 10) have given results on primary cosmic ray composition from observations using large area muon detectors with threshold energies ~GeV in association with air showers using different analysis techniques.

Some aspects of ultrahigh energy (UHE) cosmic ray astrophysics require correlated studies on the electron and muon components of air showers, namely, the search for the cosmic ray sources through gamma ray astronomy and studies on the variation of the nuclear composition of primary cosmic rays with energy. Although studies on the electron component provide basic information about the arrival direction and energy, it is the muon component that plays a crucial role in distinguishing primary gamma rays from charged cosmic ray particles and in determining the composition.

GRAPES experiment

The GRAPES experiment is located at Ooty (11.4°N lat., 76.7°E long. and 2200 m altitude), a popular mountain resort town in southern India. The Gamma Ray Astronomy at PeV EnergieS Phase 2 (GRAPES-2) experiment has been designed to study the energy dependence of the composition of primary flux at energies above 10^{14} eV. The main emphasis of the experiment was to search for directional excess among 'muon-poor' showers to optimize the detection of discrete sources of ultrahigh energy gamma rays. The GRAPES-2 experiment is a natural follow up of the successful GRAPES-1 experiment (1984–87) which gave some episodic detection[11] of several X-ray binaries, such as Scorpius X1, Hercules X1, etc.

GRAPES-2 experimental system

The extensive air shower array for the GRAPES-2 consists of 100 unshielded 'electron' detectors and a 192 module 200 m^2 area shielded 'muon' detectors. The layout of the detectors is shown in Figure 1. The interdetector separation of only 10 m for the GRAPES-2 array makes it one of the most compact arrays in the world, resulting in a lower energy detection threshold and more accurate reconstruction of shower parameters including the arrival direction. The 192 muon detector modules were accommodated in 16 tunnels and then covered by a 0.3 m thick layer of concrete slab which takes the load of a 3.5 m thick layer of packed soil placed above it and provides an overburden of 600 g cm^2, which sets the energy threshold of 1 GeV for vertical muons.

The electron detectors consist of plastic detectors, 100 cm × 100 cm in area and 5 cm thick, placed inside an aluminum tank (photomultiplier tube (PMT)) from a height of 65 cm. A special feature of the GRAPES-2 array, is the use of four special purpose liquid scintillation detectors called north (N), east (E), west (W) and south (S), located on the corners of a square of side ~9 m around the array centre, which are being used for generating the fourfold shower trigger (NEWS). Each of these four detectors uses a 10 cm deep column of mineral oil based organic liquid scintillator inside an aluminum tank of 80 cm × 80 cm.

The muon detector modules have a fast response (~5 ns), high efficiency (>95%), reliable with a safe long term operation and low cost. The water Cherenkov detector consists of an aluminum tank 170 cm × 61 cm × 80 cm with a fast PMT (ETL 9807B) suspended from the top cover of the tank. The front face of the PMT is dipped in water to a depth of ~1 cm for efficient collection of Cherenkov photons. The response of the WCD module while going through muons has been studied using a muon trigger generated by two-fold coincidences between signals from two plastic scintillator pedals placed above and below the aluminum tank. The coincident pulse is applied as a gate to the charge integrating input of multichannel analyzer (MCA). The anode pulse from the PMT is connected to MCA after suitable delay. The ratio of the number of threefold to twofold coincidences is used for measuring the muon detection efficiency of the WCD module. As a rough estimate we find that for the wavelength range of 300–500 nm, the number of Cherenkov photons emitted is ~270 cm. The Cherenkov radiation is predominantly ultraviolet and hence rapidly absorbed in water resulting in a significant loss of signal. To increase the yield of detectable photons, a wavelength shifting dye is dissolved in an alkaline solution of water. This dye absorbs photons over the wavelength range 300–380 nm and re-emits photons over the range 400–500 nm.

GRAPES-3 experimental system

The current GRAPES-3 experiment comprises a total of 721 (each 1 m^2) plastic scintillator detectors planned (it is working with 421 detectors and aims for a total of 721 detectors) to be installed over a period of time, being built in-house, with the 400 detectors currently deployed at a separation of 8 m, making it the highest density EAS array as shown in Figure 2.

In Figure 2 we also see 16 squares in the northwest region, each of which represents a four-layer muon tracking detector. Each layer consists of 58 proportional counters, each 6 m long with 10 cm × 10 cm cross-sectional area. This large area muon detector has been designed for studies on the composition[12] of primary cosmic rays and the cosmic sources of UHE gamma rays. Large area muon detector is also required for observations on muons produced by lower energy protons[13] which are affected by phenomena occurring on the Sun, such as solar flares and coronal mass ejections leading to magnetic disturbances around the Earth.

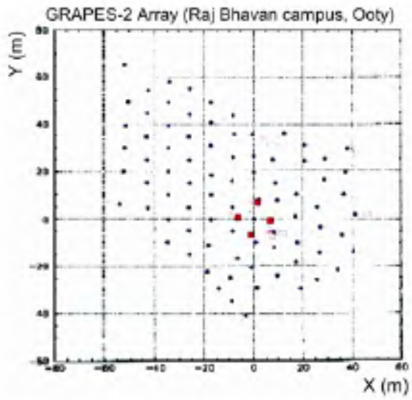

Figure 1. Layout of the detectors.

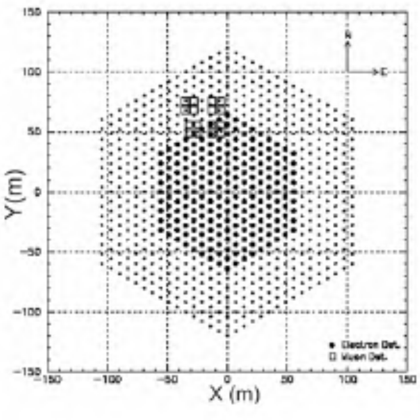

Figure 2. Layout for GRAPES-3 detectors.

The scintillator detector

The scintillation counter is also called shower detector. Each of the scintillation counters consists of four blocks of plastic scintillator, each 5 cm thick and 50 cm × 50 cm in area which are put inside a container and covered by a rain cover, both of which are made of aluminium of 0.8 mm thickness as shown in Figure 3. The scintillators are viewed by a 5 cm photomultiplier tube (PMT) model ETL9807B mounted on top of a trapezoidal-shaped aluminum cone, with its face at a height of 60 cm above the scintillator surface. The inner surfaces of the tank and the cone have been painted with super white (TiO_2) paint to increase the efficiency for collection of diffuse photons at the PMT. The detector is mounted on a 40 cm height stand, as shown in Figure 3 to raise it well above the flowing rain water. Figure 3 is a simulation of the electronic detector using Geant4 package. We can see a muon entering and further losing its energy. In this arrangement, a small muon telescope can be placed under the detector for single particle (muon) calibration. In a scintillation detector, whenever a charge particle passes through the scintillator, it emits photons which are reflected by the internal surface of the container, and collected by a photomultiplier tube. The PMT is a transducer, which converts photons into an electric signal. The measurement of these signals provides information on energy deposition and the arrival time of the charged particle.

The signal from each PMT is divided and sent to a discriminator and an ADC (analog-to-digital converter) module. The discriminator has two outputs, one of which is sent to a TDC (time-to-digital converter) module and the other is used to generate event triggers. At GRAPES-3 experiment the detectors are placed with a separation of 8 m on a hexagonal pattern. If we consider two scintillator detectors and assume the shower direction is vertical, then particles reach both the detectors at the same time. However, if the shower arrives at an angle θ with respect to the vertical direction, then the particles would reach the nearer detector first and then after some delay, the farther detector. The time difference is given by $d\sin(\theta)c$, where d is the distance and c is velocity of light. Time to digital converter is used to measure the time intervals between the arrival of particles and this information in turn is used to obtain the arrival direction.

Data recording system

The block diagram shown in Figure 4 is the general overview of the data recording system of the GRAPES-3 experiment. The analog pulses from each scintillation detector are taken to the central control room using a 230 m long 50 Ω impedance cable. Then it is passively split into two parts, the first part is coupled to a channel of ADC through an additional cable delay of 80 m. The second part of the pulse is converted into a digital pulse through a discriminator for further processing. One digital output pulse from the discriminator is sent to a channel of the TDC and a second digital TTL output is used for generating Level-0 trigger. Here we adopt two different trigger conditions, which are called the Level-0 and Level-1 trigger. The Level-0 trigger is the first level trigger which is used to initiate the digitization in ADCs and TDCs based on a 3-fold coincidence amongst the inner 127 detectors (the inner circle of detectors is needed only to optimize the selection of showers with cores incident within the array). Despite the selection of showers based on 3-line trigger, the distribution of shower cores is expected to be uniform; the 3-line trigger selects a significant number of small but local showers and also very large showers whose cores are away. Therefore an additional condition has been imposed on the shower selection, namely a requirement that at least 11 out of 127 detectors should have a signal due to passage of shower particles. Level-1 trigger is used as master trigger for the recording of data. For every Level-1 trigger, the pulse charge stored in ADCs and the pulse arrival time stored in TDCs and the absolute arrival time of the shower are recorded. A fast clear signal is generated 2.5 μs after the Level-0 trigger if the Level-1 is not generated. Generation of 'fast clear' indicates that the shower does not meet the Level-1 criteria and therefore is not to be recorded. The fast clear is used to reset the ADCs and TDCs and make the system ready for recording the next shower.

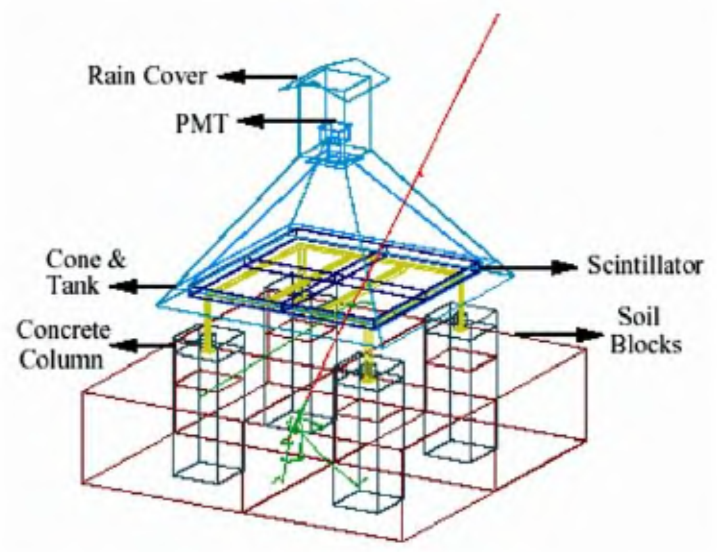

Figure 3. Simulation of the detector using Geant-4.

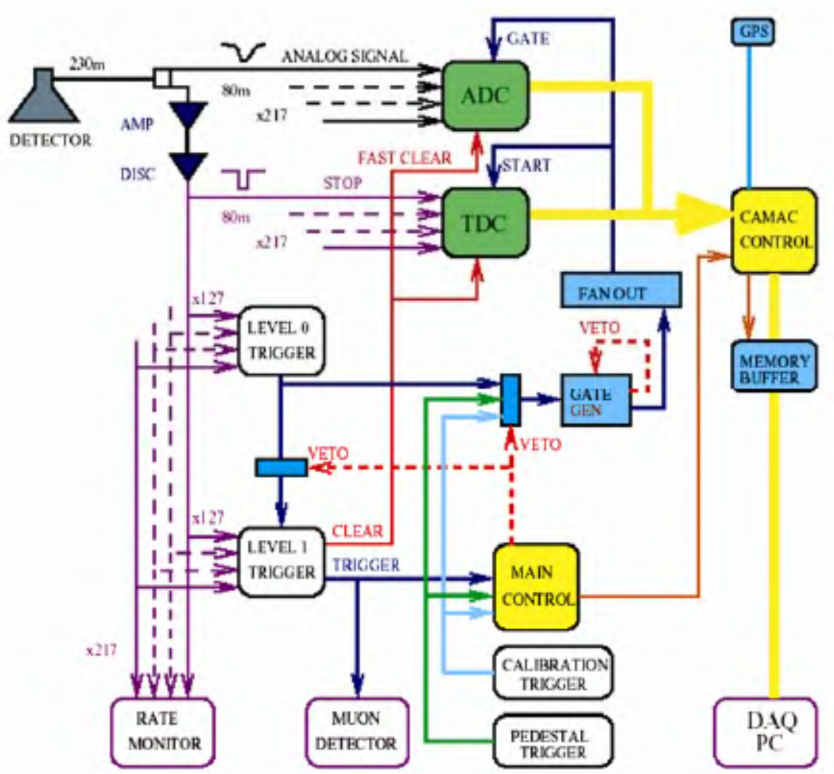

Figure 4. Block diagram for the data acquisition system.

The large muon detector

The basic element of the GRAPES-3 muon detector is proportional counter (PRC). This PRC is a 600 cm long, mild steel, square pipe with a crosssectional area of 10 cm × 10 cm and a wall thickness of 2.3 mm. The muon detector module with a sensitive area of 35 m^2 consists of a total of 232 PRCs arranged in four layers, with alternate layers placed in orthogonal directions. Two successive layers of PRCs are separated by 15 cm thick concrete, consisting of 60 cm × 60 cm × 15 cm blocks. The vertical separation of two layers of PRCs in the same plane is 50 cm which allows the muon track direction to be measured to an accuracy of ~6° in the projected plane. Above the first layer is placed a thick concrete layer of ~550 g cm^2 to achieve an energy threshold of 1 GeV for the vertical muons and we know that the electrons will be absorbed in this thickness. This huge load of 2.4 m thick concrete absorber is supported by the robust structure of the PRCs and these concrete blocks have been arranged in the shape of an inverted pyramid to achieve an energy threshold of 1 (sec θ) GeV for muons incident on the detector with zenith angle θ (up to 45°) group of four such modules separated by a horizontal distance of 130 cm at the base constituting one super module. At the bottom, a single 30 cm thick, 16 m × 16 m concrete block is cast on the ground which serves as the floor for the super module. This has been done for the uniform distribution of nearly 1200 tonnes load of the absorber in a super module to the soil below.

Due to its dense detector configuration and the presence of a very large area tracking muon detector and its high altitude, and in view of its expansion, the GRAPES array would offer advantages. These include enhanced ability to measure cosmic ray composition, its spectral shape and sensitivity to episodic phenomena. For astrophysical observations, the unique location of Ooty near the equator offers a view of both northern and southern skies, including the galactic centre region.

1. Rene A. Ong, 29th International Cosmic Ray Conference (ICRC), Pune, 2005, vol. 10, pp. 329–356.
2. Thomas K. Gaisser, *Cosmic Rays and Particle Physics*, Cambridge University Press, 1991.
3. Kampert, K. H., 26th International Cosmic Ray Conference (ICRC), Salt Lake City, Utah, 1999, vol. 3, p. 159.
4. AGASA results, Aspen 2005:aspen2005 sakaki.pdf
5. Gupta, S. K. *et al.*, 30th ICRC, Merida, Mexico.
6. William Galbraith, *Extensive Air Showers*, Butterworths Scientific Publication, London, 1958.
7. Aglietta, M. *et al.*, in Proceedings of the 26th ICRC, Salt Lake City, Utah, 1999, Vol. 1, p. 230.
8. Antoni, T. *et al.*, *Astropart. Phys.*, 2002, **16**, 245.
9. Tonwar, S. C., *Bull. Astron. Soc. India*, 2002, **30**, 147.
10. Hayashi, Y. *et al.*, in Proceedings of the 27th ICRC, Hamburg, 2001, p. 111.
11. Gupta, S. K. *et al.*, *Phys. Rev.*, 1993, **D48**, 3463.
12. Hayashi, Y. *et al.*, Proceedings of the 26th ICRC, Salt Lake City, 1999, vol. 1, p. 276.
13. Nonaka, T. *et al.*, *Phys. Rev. D*, 2006, **74**, 052003.

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