Abstract

The GRAPES-3 is a unique, extensive air shower experiment consisting of 400 scintillator detectors spread ~~over an area of~~ 25000 m2 and a 560 m2 muon telescope. The experiment located at Ooty, India, has been collecting data for the past two decades. The unique capabilities of GRAPES-3 have allowed the study of cosmic rays over energies from a few TeV to tens of PeV and beyond. The measurement of the directional flux of muons ($E_\mu \geq 1$ GeV) by the large muon telescope permits an excellent gamma-hadron separation ~~to be made, which then in turn~~ **, which then** becomes a powerful tool in the study of multi-TeV γ-ray sources and the composition of primary cosmic rays. However, the high precision measurements also enable studies of transient atmospheric and interplanetary phenomena such as those produced by ~~the~~ thunderstorms and geomagnetic storms. In this ~~talk~~ some of the exciting new recent results would be presented and updates provided on various ongoing analyses. **(SUGGESTION OF REWRITING; ACTIVE VOICE AND CONCISE: This paper presents some exciting new and recent results, including updates on various ongoing analyses.)**

1 Introduction

Cosmic rays (CRs) were discovered by V.F. Hess more than a century ago. Historically many experiments have studied them in the extraordinary energy range of 100 MeV–100 EeV to understand the origin and properties of CRs. The broad span of **the** primary energy spectrum has a power-law dependence with multiple spectral breaks namely knee and ankle at various energies. The CRs are predominantly composed of protons (~90%), helium (~9%), and heavier elements up to iron, attributing to the remaining 1%. The energy spectrum and nuclear mass composition studies are the primary objectives of any CR experiment. ~~The~~ **Cosmic** ray detection can be broadly classified into two categories, namely direct and indirect detection methods. The CRs can be detected directly using detectors aboard space probes and balloon flights. However, this is possible up to 100 TeV. Beyond this energy, ~~the~~ direct observation is limited by **the** rapidly falling flux of CRs, detector size, and exposure time. Above 100 TeV, the CRs can be detected indirectly by using **the** extensive air shower (EAS) phenomenon in which the primary cosmic ray (PCR) develops into a shower of particles in the Earth's atmosphere that can be detected at the surface using an array of particle detectors. The GRAPES-3 consists of an array of plastic scintillators and a large area tracking muon telescope for CR studies in a broad energy range of 1 TeV–10 PeV. Because of its tightly packed configuration with ~~the~~ **a** sensitive area of ~2%, larger ~~compared to~~ **than** other experiments (< 1%), the energy threshold is brought down as low as 1 TeV. Also, the muon telescope helps to differentiate gamma and hadron-initiated EASs for composition and gamma-ray astronomy studies. The GRAPES-3 energy spectrum and mass composition measurements may provide good overlap with the measurements from direct and indirect detection methods by other experiments. ~~**Being close to equator**~~ ~~(~~**Rewrite the last statement t is dangling modifier**~~)~~, the GRAPES-3 ~~is able to~~ **can** look into ~~both~~ the northern and southern hemispheres with reasonably good coverage. The scientific objectives of GRAPES-3 span into multi-energy domain**s** such as atmospheric acceleration, solar phenomena, energy spectrum and composition studies of CRs, and multi-TeV gamma**-**ray astronomy. This paper discusses some published results and preliminary results from the various ongoing **analyses**. (**SUGGESTION OF REWRITING: This paper discusses published and preliminary results from the various ongoing analyses.)**

2 The GRAPES-3 experiment

The Gamma Ray Astronomy at PeV EnergieS – 3 (GRAPES-3) is a ground**-**based EAS experiment. It is located at Ooty, India (11.4◦N, 76.7◦E) at an altitude of 2200 m above mean sea level. The near**-**equatorial placement of the experiment provides a unique advantage for measurements covering both northern and southern hemispheres significantly. The GRAPES-3 consists of two detector element**s,** namely (i) high**-**density large area EAS array and (ii) large area tracking muon telescope (G3MT) as shown in Figure 1. The EAS array is designed using 400 plastic scintillators**,** each with an effective area of 1 m2 . The scintillators are placed in a hexagonal geometry with an inter-detector separation of 8 m as seen in Figure 1, covering an area of 25000 m2 . Due to its tightly packed detector configuration~~, it is possible to measure~~ **, measuring** PCRs of energy from 1 TeV to 10 PeV **is possible**. Each scintillator records **the** energy deposit and first arrival time of the passing particle ~~**with**~~ respective to an EAS trigger generated **by the array (This is a Squinting modifier, I suggest change or move the modifier)** itself. ~~These~~ **This** information can be reconstructed offline to get the properties of the PCRs. A detailed report on the detector and data recording system can be found here [1]. Everyday, the GRAPES-3 records about 3.5 million EASs in the above-mentioned energy range. The second detector element is G3MT which is built using 16 muon telescopic modules as shown in Figure 1. Each muon module has an area of 35 m2 . **A p**roportional counter (PRC) is a gaseous detector used to build the G3MT. Each PRC is 600×10×10 cm3 mild steel tube which is sealed and filled with **a** P10 gas mixture (90% argon and 10% methane). A 100**-**micron thick tungsten wire at the center acts as **an** anode**, whereas** the metal body is **the** cathode. Each muon module consists of four layers of PRCs. Each layer is arranged with 58 PRCs. The layers are sandwiched by a 15 cm thick concrete slabs (**SUGGESTING REWRITING: A 15 cm thick concrete slab sandwiches the layers**). Also, the alternate layers are placed orthogonal to each other. **This** ~~**particular configuration allows to reconstruct**~~ **configuration allows reconstruction of** the detected muons in 169 directions that can be used for physics studies. Above the topmost PRC layer, 2 m thick concrete slabs are placed in an inverted pyramidal shape to provide an energy threshold of sec(θ) GeV for muons coming at zenith θ. The primary role of G3MT is to measure the muon content from the EAS**, which is an excellent** ~~w that are very good~~

proxy for differentiating gamma and hadron-initiated EASs **and measuring the** ~~also for the measurement of~~ nuclear mass composition of PCRs. There is a secondary data recording system to record the angular muon flux ~~when there is no EAS trigger~~. **when no EAS trigger exist**. ~~These muons are predominantly produced by the EASs~~ **The EASs predominantly produce these muons** in the energy range of 10 GeV–10 TeV. The G3MT collects about 4 billion muons per day. This particular measurement is an ideal choice for studies of transient events such as thunderstorms and solar storms, cosmic ray modulation in ~~the~~ interplanetary space, etc. More details about the detector instrumentation can be found here [2].

3 Physics results

The primary objectives of GRAPES-3 experiment span over many orders of magnitudes in energy**,** starting from 1 GeV to 10 PeV. These objectives can be classified into their respective physics domains**,** namely (i) atmospheric acceleration, (ii) solar studies, and (iii) cosmic ray studies. Some published and preliminary results in the above categories are discussed briefly in the following subsections.

3.1 Atmospheric acceleration

Thunderstorm studies are emerging as one of the exciting areas of physics using cosmic ray secondaries. Especially muons are **the** ideal choice for studying these phenomena since they ~~loose~~ **lose** only a small and constant energy loss by ionization. One of the biggest mysteries in this field is ~~**about**~~ the development of more than **a** billion volts in the thundercloud**,** which was predicted by C.T.R. Wilson almost a century ago [3]. The G3MT records about 50 significant thunderstorm events every year. One of the biggest thunderstorm event was recorded on 1 December 2014 that lasted for 18 minutes. The muon intensity dropped in 45 contiguous directions out ~~of total of~~ 169 directions. By combining the muon flux from those 45 directions, a clear deficit of 2% was seen with a significance of 10σ whereas the total significance was about 20σ. Detailed **M**onte **C**arlo simulations allowed **us** to estimate the peak potential of the thundercloud to be (0.90±0.08) GV. Subsequent analyses on **the** shorter time scale of 2-minute muon exposure gave a conservative estimate ~~on~~ **of** peak potential ~~to be~~ **of** 1.3 GV [4]. ~~A~~ **C**lear evidence of cloud movement from east to west was seen in **the** 2-minute exposure map and ~~also~~ in electric field measurements that ~~yields an estimation of~~ **estimate** linear and angular velocities to be 1 km·min−1 and 6.2◦ min−1**,** respectively. The cloud height was estimated to be 11.4 km by combining linear and angular velocities. Considering the cloud coverage was in the entire field of view (FOV) of G3MT, the thundercloud should have a radius ≥11 km ~~that implies~~ **, implying** an area of ≥380 km2 . Similarly, **we estimated** the electrical properties of the cloud ~~was estimated~~ by assuming a parallel-plate capacitor with an effective capacitance of ≥0.85 μF. a peak potential of 1.3 GV would require a total charge of ≥1100 C and energy of ≥720 GJ. **Considering the rise time 6 min** **(DANGLING MODIFIER, REWRITE TO AVOID THE DANGLING MODIFIER)** this thundercloud would have delivered a power of ≥2 GW. Though the G3MT ~~is being~~ **has been** operated for more than two decades, the thunderstorm studies may be carried out using electric field measurements only since April 2011 after ~~the installation of~~ **installing** four electric field mills. A total of 487 significant thunderstorm events were identified ~~during~~ **from** April 2011 to December 2020. These events were selected when $\Delta I\mu \geq 0.3\%$ and ~~observation of~~ **synchronous** time variation in the electric field measurements **were observed**. These events show a clear asymmetry in their direction when distributed over **a** coarser 9-direction configuration**,** as shown in Table 1. About 80% of the total events were recorded in the east. There is a clear asymmetry in **the** east-west compared to **the** north-south orientation. This effect can be very well understood by the muon charge ratio present in ~~**the**~~ nature. Figure 2 shows the muon charge ratio derived from the Monte Carlo simulations**,** where it can be seen clearly that the ratio is higher in the east compared to the west. This particular asymmetry in the muon charge ratio ~~is a result of~~ **results from** bending of muons in the presence of **the** geomagnetic field.

3.2 Solar studies

As ~~explained in the previous section~~ **the previous section explains**, ≥GeV angular muon flux is an ideal choice for studying transient events. On 22 June 2015**,** ~~there were~~ **a** series of coronal mass ejections (CMEs) were released ~~released~~ from the surface of the Sun. Especially the third CME had a jump of >300 km·s −1 in the solar wind velocity (VSW) and triggered a G4 class geomagnetic storm. During that time Bz component of **the** interplanetary magnetic field (IMF) had a specific structure which resulted ~~as~~ **in** a short muon burst recorded in the G3MT for 2 hours (Ref. Figure 1 & 2 of [5]). This muon burst is believed to be caused by the magnetic reconnection of IMF Bz with the geomagnetic field (GMF)**,** which lowered the cutoff rigidity for incoming PCRs. The entry of excess low**-**energy PCRs produced more EASs ~~that resulted as~~ **resulting in a** muon burst. Also, the muon burst was observed simultaneously in all nine directions**,** which indicates that this effect was localized (Ref. Figure 3 of [5]). Detailed Monte Carlo studies confirmed that the observed phenomena ~~**was**~~ **were** indeed due to **the** lowering of cutoff rigidity by **the** interaction of IMF with GMF [5]. Interestingly the muon burst was observed 32 minutes after the arrival of IMF. Studying such geomagnetic storm events may help us to understand its propagation and effects in the interplanetary medium. As mentioned before**,** the G3MT **has been** ~~is being~~ continuously operated for **over** ~~**more than**~~ two decades. **We recorded about** 80 such geomagnetic storm events having various amplitudes and delays ~~**were recorded**~~ during this period. A multi-parameterization study involving the observed muon intensity and the solar wind parameters measured at L1 point may help better **understand future** solar storms. ~~**for better understanding of future solar storms.**~~ In a recent study**,** ~~it was~~ **we** found that geomagnetic storm events were also recorded in the scintillator detectors. ~~As discussed in the previous section, the GRAPES-3 EAS array consists of 400 plastic scintillator detectors~~. Each detector counts **the** number of particles (~200–300 sec−1) above a certain threshold (few MeVs). Here, the detection includes ~~**various**~~ particles such as muon, gamma, electron, hadron, etc. Unlike G3MT, the scintillators do not record the direction of the passing particle. ~~**It is to be**~~ **We** noted that scintillator rates are prone to temperature effect**s** due to photomultiplier tubes used ~~**in them**~~. However, one can make a quantitative selection of detectors having less temperature dependence for **a** better signal**-to-**noise ratio. Figure 3a shows the background corrected scintillator rates for selected detectors after applying stringent cuts. Figure 3b shows the background corrected scintillator rate for **the** fiber detector ~~**in comparison with**~~ **compared to** Monte Carlo simulation. It is quite interesting to note that the scintillator rate ~~**has**~~ recorded ~40% higher amplitude ~~**compared to**~~ **than** G3MT. ~~**From**~~ **The** Monte Carlo simulations~~, it was~~ found that the recorded scintillator rate count ~~**composes**~~ **composed of** 58% muons, 11% gamma, 29% electromagnetic components, and **the** remaining ~~by~~ hadrons. The estimated scaling factor and delay are consistent with the G3MT's observation. This particular data may allow ~~to identify~~ **identifying** weak geomagnetic storm events.

3.3 Cosmic ray studies

3.3.1 Improvements in angular resolution Precise reconstruction of EAS direction is ~~**an important**~~ **essential** aspect in studies of CR origin and gamma**-**ray astronomy. It is well understood that **the** shower front has a curvature. Conventionally it has been corrected by applying a constant curvature (0.215 ns·m−1) to the shower front**,** and then a planar fit is performed to estimate the EAS direction. In a recent study**,** it was found that shower front curvature has a strong dependence on shower size and shower age [6]. In this work**,** the curvature dependences were studied in great detail and corrected to get **an** improved fit. **We achieved an** ~~**An**~~ angular resolution starting from 47' at >5 TeV to 10' at >500 TeV ~~**was achieved**~~. These improvements were **also** achieved ~~**also**~~ because of better time measurement using HPTDC and real**-**time estimation of time offset using a statistical method called "random walk". The GRAPES-3's angular resolution is comparably better than other EAS arrays such as ARGO-YBJ, Tibet ASγ, and HAWC**,** which are located at a higher elevation**s** than GRAPES-3.

MAJOR COMMENT: THE LAST PARAGRAPH IS STRONG AND MUST BE CLARIFIED AND STRENGTHENED IN CONTEXT. Give values for other experiments and compare accordingly. Also, compare with the sentence from lines 213 to 215 and provide coherence and consistency. Keep sequence too. First, clarify the angular resolution

determination of GRAPES-3 and details, then compare with other observatories and conclude about resolutions respecting to.

3.3.2 Cosmic ray shadow of the Moon

Another important aspect of EAS array is ~~to understand the pointing accuracy of the direction reconstruction~~ **is understanding the direction reconstruction's pointing accuracy**. One reliable and widely accepted method is to use **the** cosmic ray shadow of the Moon. The Moon is a big obstacle with an angular diameter of about 0.5° for incoming PCRs. **A study** of this shadowing effect using the EAS array helps to calibrate its angular resolution and pointing accuracy. **We used the EAS data collected during 2014–2016**. Figures 4a–d show the Moon shadow as a function of angular distance from the center of the Moon for energies above 5, 50, 100, and 200 TeV. The angular resolution using this method was estimated to be $(0.83\pm0.09)^\circ$ at >5 TeV with a significance of 9.1σ (Figure 4a). This improves to $(0.29\pm0.06)^\circ$ at >200 TeV with a significance of 3.1σ (Figure 4d). These results are consistent with the earlier analysis described in the previous subsection and comparable with other experiments that are located almost twice the altitude of GRAPES-3 (Figure 4e). We estimated the ~~**The**~~ pointing accuracy of the EAS array along right ascension (α) and declination (δ) was estimated to be $(0.032\pm0.004)^\circ$ and (0.090 ± 0.003)**,** respectively (Figure 4f). More details can be found in the detailed report [7].

3.3.3 Primary energy spectrum and mass composition

As mentioned earlier, the GRAPES-3's energy spectrum measurement in the energy range of 1 TeV–10 PeV may provide an overlap between low and ultra-high energy measurements from other experiments. For the preliminary study, 1.47×107 EASs recorded ~~during~~ **from** January 2014 to October 2015 were selected after imposing quality cuts to enrich the data quality. The EASs were selected with the following quality cuts: (i) successful direction and Nishimura-KamaraGreisen reconstruction, (ii) Cores within the fiducial area (7850 m2) of 50 m radius from the center of the array, (iii) shower age 0.2104**,** at which the trigger efficiency is above 90%. The selected EASs were translated from shower size to energy with ~~the aid of~~ Monte Carlo simulations. CORSIKA v76900 was used with QGSJETII-04 and FLUKA for high and low**-**energy hadronic interaction models. The EASs were simulated in the energy range of 1 TeV–10 PeV with spectral index γ=–2.5 for mass species proton, helium, nitrogen, aluminium, and iron. Each mass specie**s** has 1.2×108 simulated EASs. **We restricted the** zenith angle ~~**was restricted**~~ to 45° . The Monte Carlo data set was subjected to detector simulation and reconstructed ~~**back**~~ to get the primary properties ~~**as done**~~ for the experimental data. Figure 5a shows the measured proton spectrum in comparison with ~~**other**~~ **different** experiments **(MAJOR COMMENT HERE: Add references and compare with the values of these works and/or clarify better).** ~~It~~ **We** can be seen that the GRAPES-3 proton spectrum has a reasonably good overlap with other measurements. A notable feature can be seen at 208.5±1.6 TeV where the spectrum hardens from γ_1=–3.14 to γ_2=–2.54. More details may be found in the proceeding of the contributed talk in this symposium (F. Varsi et al.).

4 Conclusion

Some published and preliminary results of GRAPES-3 were presented during the symposium covering atmospheric acceleration, solar studies, energy spectrum and composition, angular resolution, cosmic ray anisotropy, etc. The muon imaging technique allowed **us** to measure 1.3 GV electric potential in one of the massive thunderclouds recorded by the muon telescope, providing many insights into the electrical and geometrical properties of the thundercloud. A collection of 487 significant thunderstorms indicated a clear directional asymmetry which ~~**can be explained by the muon charge asymmetry**~~**. the muon charge asymmetry can explain**. Similarly, the geomagnetic studies and ~~its~~ **their** implications on cosmic ray flux and identification of many such events using the GRAPES-3 muon telescope may provide key inputs in **the** advancement of space weather prediction. Recent studies revealed that the GRAPES-3 scintillators also provide vital information in understanding geomagnetic storms, especially ~~the events~~ **those with weak signals** that ~~**can not be detected by**~~ the muon telescope **can not detect**. ~~The validation of earlier~~ **Earlier** studies on angular resolution of the GRAPES-3 EAS array ~~was carried out~~ **were validated** using **the** cosmic ray shadow of the Moon. The angular resolution was estimated to be (0.83±0.09)◦ at >5 TeV and improves to (0.29±0.06)◦ at >200 TeV, confirming the earlier studies using different techniques. This angular resolution is comparable to the other experiments that are located almost twice the altitude of GRAPES-3. **(CHECK THE COMMENTS AT LINES 194-196, 213-215, and 239-240. It is comparable or comparable better? If the angular resolution is better, the fact deserves more details and to be strengthened as result. On the other hand, a comparison must have the comparing numbers and context.)** The pointing accuracy was estimated to be (0.032±0.004)◦ and (0.090±0.003)◦ along the right ascension and declination**,** respectively. ~~**By using**~~ **Considering** the EASs collected **data** from January 2014 to October 2015, the proton energy spectrum was derived ~~with the aid of~~ **employing** Monte Carlo simulations using CORSIKA **(The point in the last sentence is do not use to much USING and avoid wordy).** The measured spectrum was found to have **a** reasonably good overlap with other measurements. ~~Also~~ **We found** a notable spectral break ~~was found~~ at ~208 TeV. Currently, the GRAPES-3 muon telescope is being upgraded to double its area and sensitivity**,** which is expected to improve its physics potential.

Acknowledgements

We thank D.B. Arjunan, A.S. Bosco, V. Jeyakumar, S.Kingston, K. Manjunath, S. Murugapandian, S. Pandurangan, B. Rajesh, V. Santhoshkumar, M.S. Shareef, C. Shobana, and R. Sureshkumar for their efforts in maintaining the GRAPES-3 experiment.