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Small-scale anisotropy in the cosmic ray flux observed by GRAPES-3 at TeV energies

M. Chakraborty,[a,*] S. Ahmad,[c] A. Chandra,[c] S.R. Dugad,[a] U.D. Goswami,[l] S.K. Gupta,[a] B. Hariharan,[a] Y. Hayashi,[b] P. Jagadeesan,[a] A. Jain,[a] P. Jain,[d] S. Kawakami,[b] H. Kojima,[e] S. Mahapatra,[i] P.K. Mohanty,[a] R. Moharana,[j] Y. Muraki,[g] P.K. Nayak,[a] T. Nonaka,[h] A. Oshima,[e] B.P. Pant,[j] D. Pattanaik,[a,i] G.S. Pradhan,[k] M. Rameez,[a] K. Ramesh,[a] L.V. Reddy,[a] R. Sahoo,[k] R. Scaria,[k] S. Shibata,[e] K. Tanaka,[f] F. Varsi[d] and M. Zuberi[a]

[a] *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[b] *Graduate School of Science, Osaka City University, Osaka 558-8585, Japan*
[c] *Aligarh Muslim University, Aligarh 202002, India*
[d] *Indian Institute of Technology Kanpur, Kanpur 208016, India*
[e] *College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*
[f] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima 731-3194, Japan*
[g] *Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan*
[h] *Institute for Cosmic Ray Research, Tokyo University, Kashiwa, Chiba 277-8582, Japan*
[i] *Utkal University, Bhubaneshwar 751004, India*
[j] *Indian Institute of Technology Jodhpur, Jodhpur 342037, India*
[k] *Indian Institute of Technology Indore, Indore 453552, India*
[l] *Dibrugarh University, Dibrugarh 786004, India*

E-mail: 10medha.riya@gmail.com, pkm@tifr.res.in

Cosmic ray (CR) anisotropy of several scales have been observed over the last decade by a number of experiments located in the Northern and Southern hemispheres. The GRAPES-3 experiment, located at 11.4° N can observe a significant portion of both the hemispheres and covers about 56% of the sky at TeV energies. Several small-scale anisotropic features, with a strength of $\sim 10^{-4} - 10^{-3}$, have been observed using four years of GRAPES-3 data collected within a period of 2013-2016, by using the method of time-scrambling. Two striking hot-spot regions have been observed with a significance of more than 4σ. These structures are consistent with the observations reported by Milagro, ARGO-YBJ and HAWC. These structures, their characteristic features and a comparison of results from other experiments are described in this work.

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1. Introduction

Cosmic rays (CRs) are charged particles that experience deflections as they traverse the random magnetic field present in the interstellar medium. Consequently, their distribution on Earth appears isotropic. Nevertheless, in recent years, various experiments situated at different latitudes have detected anisotropies in cosmic rays across different angular scales and energy ranges, typically on the order of $\sim 10^{-4}$-10^{-3}. Ground-based cosmic ray air shower experiments, located in the Northern hemisphere such as Tibet-ASγ ([1, 2]), ARGO-YBJ ([3]), Milagro ([4]), HAWC ([5]), and in the Southern hemisphere such as IceCube ([6]), have observed large-scale structures characterized by a prominent dipolar component in the TeV-PeV energy range.

The Milagro experiment initially reported a small-scale anisotropy characterized by an angular width of less than 60°. This observation revealed excesses in two distinct regions, namely region A and region B, with an excess magnitude of approximately 6×10^{-4} and 4×10^{-4}, respectively ([7]). As the Milagro experiment is situated at a latitude of 36°N, it could only observe the upper portion of region A, centered around $\alpha \approx 69.4°$ and $\delta \approx 13.8°$. On the other hand, region B was identified as a continuous structure spanning the declination range of $10° \leq \delta \leq 50°$, with a right ascension range of $117° \leq \alpha \leq 141°$. The ARGO-YBJ experiment also detected these regions, along with two additional regions labeled as "3" and "4" ([8]). Region 3 extended across the declination bands within $234° \leq \alpha \leq 282°$, while region "4" was observed with $200° \leq \alpha \leq 216°$ and $24° \leq \delta \leq 34°$, resembling region "C" observed by HAWC ([9]).

A comprehensive analysis combining data from HAWC and IceCube over the entire sky unveiled the two primary anisotropy structures within region "A" and "B," with region "B" appearing to extend across the complete declination range ([13]). Various models have been proposed to explain the origins of these structures. Some suggest that turbulent magnetic fields within the cosmic ray scattering length ([10]) contribute to these structures. Another set of models propose that the anisotropies result from magnetic reconnections in the heliosphere ([11]). Furthermore, certain models propose the presence of nearby cosmic ray sources ([12]). This work describes the observation of small-scale anisotropy by GRAPES-3 using four years of scintillator data.

2. GRAPES-3 experiment

The GRAPES-3 experiment, also known as Gamma Ray Astronomy at PeV Energies Phase-3, is situated in Ooty, India, at coordinates 11.4°N, 76.7°E, and an altitude of 2200 meters above sea level. The extensive air shower (EAS) array of GRAPES-3 comprises 400 plastic scintillator detectors, each with a surface area of 1 square meter. These scintillator detectors are arranged in a hexagonal pattern, covering a total area of 25000 square meters, with a distance of 8 meters between neighboring detectors. They record both the densities of particles and the arrival times of particles when an air shower is triggered within the GRAPES-3 array, the details of which are described in [14]. Additionally, GRAPES-3 includes a tracking muon detector, which spans an area of 560 square meters and consists of 3712 proportional counters (PRCs). The GRAPES-3 experiment operates with an almost 100% duty cycle, allowing it to record approximately 3 million showers every day. For a visual representation of the GRAPES-3 array, refer to Figure 1, which illustrates its schematic structure.

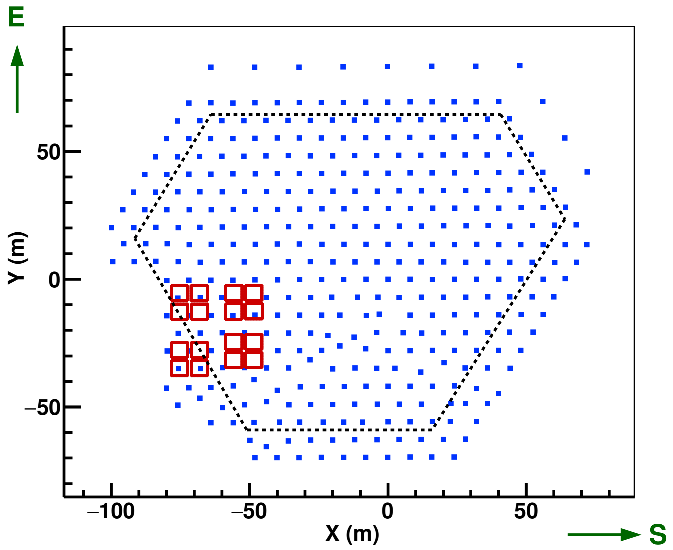

Figure 1: A schematic of the GRAPES-3 experiment.

3. Analysis

For this analysis, 4 years of GRAPES-3 data recorded from 1st January, 2013 to 31st December, 2016 was used with a total of 3.9×10^9 events, having a live time of 1273.1 days. GRAPES-3 has achieved an improved angular resolution using shower size and age dependent correction on the relative arrival times of the secondaries, due to shower front curvature as discussed elsewhere ([15],[16]). Several selection criteria were applied to select the well reconstructed showers. The showers with proper angular reconstruction and within 60° of zenith angle were selected. After applying the selection criteria, 3.6×10^9 events remained which were used for further analysis.

The search for anisotropic features is based on the estimation of a reference map having an event distribution on the Celestial sphere corresponding to isotropic CR flux. The reference map should only replicate the anisotropies arising due to detector and atmospheric effects, but not due to astronomical effects. Atmospheric effects introducing a variation in the event rate, and the detector acceptance create challenges in the observation of anisotropy by leading to a non-uniform sky exposure. Breaks in the DAQ can also give rise to spurious anisotropies as described in [17]. It is difficult to replicate all such effects accurately in simulation. Thus, the reference is estimated from the data itself using the method of time-scrambling as described in [18] and has been previously used by ARGO-YBJ and IceCube. An overview of the method is described here. Each recorded event is assigned a random time from the recorded event time sample within a time window Δt by keeping the zenith and azimuth fixed. This changes the right ascension of the event by keeping its declination fixed and results in removal of structures within angular scale of $\Delta t \times 15°/hr$ of RA. The choice of random time from the event time sample ensures that the effects of event rate variation and breaks in DAQ are also present in the reference map. Each event is assigned 20 such random times in order to reduce statistical fluctuations. All the events are filled into the reference map which is then re-weighted by a factor of 1/20. These maps have a high level of Poisson fluctuation in the number of events distributed over the pixels, thus showing no discernible anisotropic patterns.

These maps were smoothed using top-hat function of radius 10°, which correlates the number of events in neighbouring bins but shows the anisotropic structures. The structures that we are trying to observe span over few tens of degrees, so, a choice of a 10° smoothing radius ensures that these structures are not integrated over. The relative intensity is then calculated using,

$$\delta I = \frac{N_{ij} - N_{oj}}{N_{oj}} \tag{1}$$

where N_{ij} and N_{oj} are the number of events in the j-th pixel of data and scrambled maps respectively. The pixel-wise significance is calculated using the well-known Li-Ma formula [19].

4. Results and discussions

In Figure 2, two distinct anisotropic features have been identified and labeled as "A" and "B". Figure 3 shows the unsmoothed number of events and the corresponding excesses as a function of right-ascension. The variation in number of events caused due to detector and atmospheric effects are well replicated by the time-scrambling algorithm.

Region A exhibits a circular structure with a tail-like projection. It is observed within a right ascension range of approximately 50° to 90° and a declination range of about -15° to 30°. The relative excess number of events in this region is $(6.5 \pm 1.3) \times 10^{-4}$, and its significance measures at 6.8σ. On the other hand, region B represents an elongated structure spanning approximately 110° to 140° of right ascension, covering nearly the entire declination range. The total excess of events within region B is $(4.9 \pm 1.4) \times 10^{-4}$, with a significance of 4.7σ. These findings align with observations made by other air shower experiments such as Milagro [4], ARGO-YBJ [3], and HAWC [9]. A zoomed view of these structures are shown in Figure 4.

5. Acknowledgements

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References

[1] M. Amenomori et. al. 2006, Science, 314, 439,

[2] M. Amenomori, et al. 2017, Astrophys. J., 836, 153,

[3] Bartoli, B., Bernardini, P., Bi, X. J., et al. 2018, ApJ, 861,93

[4] Abdo, A. A., Allen, B. T., Aune, T., et al. 2009, ApJ, 698,2121

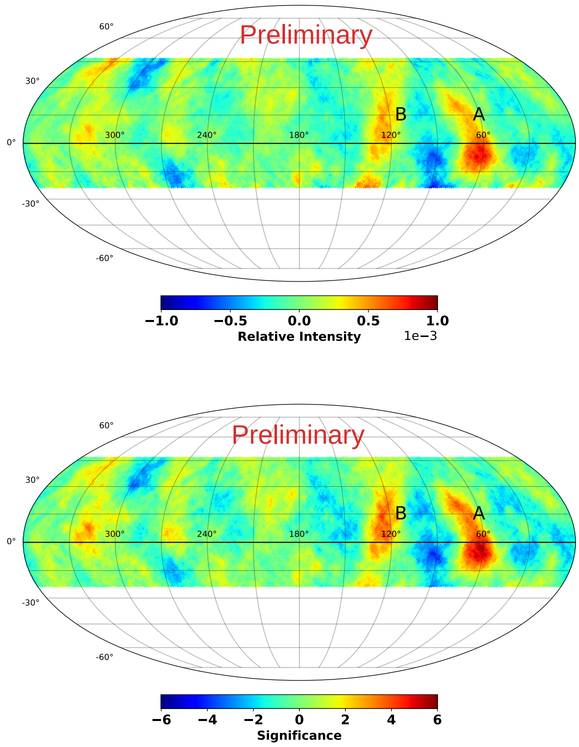

Figure 2: Anisotropy and significance observed with a scrambling window of 4 hrs and a smoothing radius of 10°.

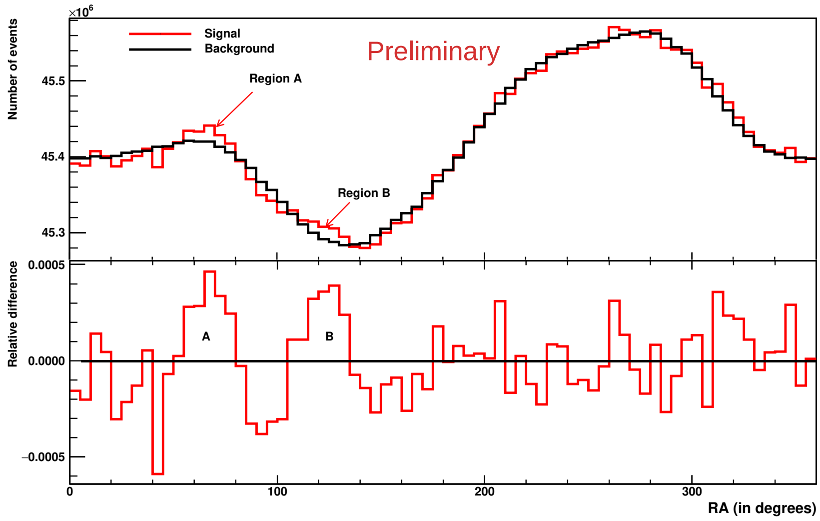

Figure 3: Anisotropy as a function of right ascension. The systematic rises show the regions A and B excesses.

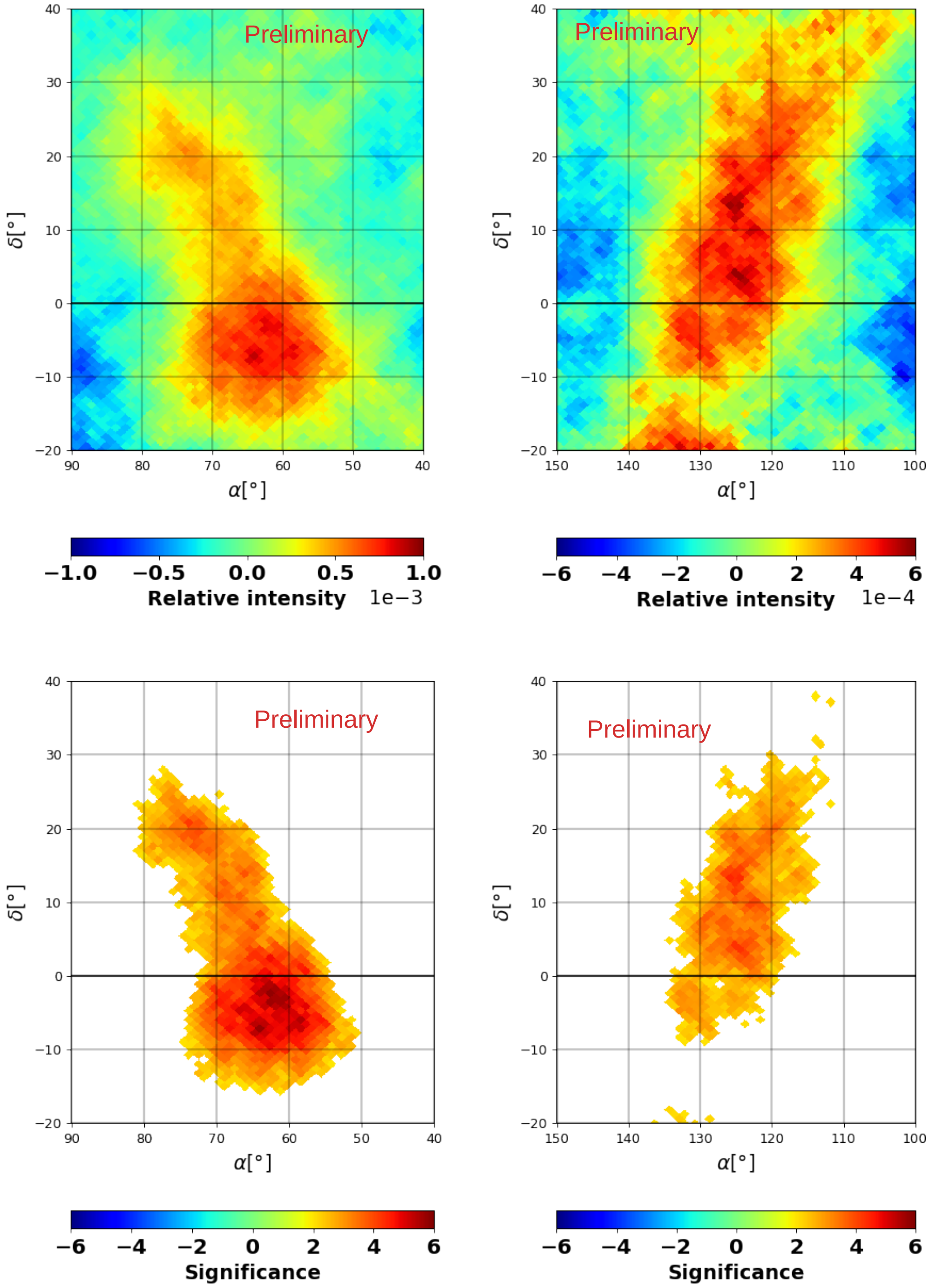

Figure 4: Anisotropy and significance observed with a scrambling window of 4 hrs and a smoothing radius of 10°.

[5] Abeysekara, A. U., Alfaro, R., Alvarez, C., et al. 2019, ApJ,871, 96,

[6] M. G. Aartsen et. al. 2016, The Astrophys. J., 826, 220

[7] A.A. Abdo et. al. . 2008, Phys. Rev. Lett., 101, 221101,

[8] B. Bartoli et al. 2013, Phys. Rev. D, 88, 082001

[9] A. U. Abeysekara et. al. . 2014, The Astrophys. J., 796, 108

[10] M. Ahlers P. Mertsch. 2015, The Astrophys. J. Lett., 815

[11] Desiati, P., Lazarian, A. 2012, in American Institute of Physics Conference Series, Vol. 1436, Physics of the Heliosphere: A 10 Year Retrospective, ed

[12] M. Salvati B. Sacco. 2008, Astron. Astrophys., 485, 527,

[13] Abeysekara, A. U., Alfaro, R., Alvarez, C., et al. 2019, ApJ,871, 96

[14] S.K. Gupta et al., Nucl. Instr. Meth. A 540 (2005) 311

[15] V.B Jhansi et. al.,Journ. of Cosmol. and Astropart. Phys. 07(2020)024

[16] D. Pattanaik et. al., Phys. Rev. D 106, 022009 (2022)

[17] M. Chakraborty et. al., Proceedings of Science PoS(ICRC2021)393

[18] Alexandreas, D. E., et al. 1993, Nucl. Instrum. Meth. A, 328, 570,

[19] Li T & Ma Y 1983 Astrophys. J. 272 317-324