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Observation of Medium-Scale Anisotropy in Very-High-Energy Cosmic Rays using LHAASO-KM2A

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The intensity of Galactic cosmic rays in the arrival directions is highly isotropic; however, many cosmic ray experiments have observed weak anisotropies of various angular sizes. In this work, we report the observation of the medium-scale structures with the square kilometer array of the Large High Altitude Air Shower Observatory(LHAASO-KM2A). We have found that the positions of the excess regions, located at $\alpha \sim 315°$, $\delta \sim 21°$ (around 17 TeV), and $\alpha \sim 125$, $\delta \sim 42°$, provide compelling evidence of energy dependence within the energy range of 10 TeV to over 100 TeV. Furthermore, the evolution behaviors of energy dependence may indicate that local complex turbulent environments play a potential role in the propagation of cosmic rays, which offers a new perspective on their origin and transport of cosmic rays.

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1. Introduction

Despite the expectation that prolonged propagation in turbulent magnetic fields erases directional information, leading to isotropic galactic cosmic ray (CR) fluxes, anisotropies with amplitudes of 10^{-4} to 10^{-3} have been measured by ground-based experiments at very high energies [1–8]. This large-scale anisotropy is primarily characterized by an energy-dependent dipole. The origins of this dipole are not yet fully resolved; proposed explanations include a combination of CR source distributions, galactic diffusion, nearby sources, and the local interstellar magnetic field [9–14].

Complementing large-scale features, medium-scale excess regions (down to $\sim 10°$) have been detected across both hemispheres. Northern hemisphere observations come from Tibet ASγ[15], Milagro [16], ARGO-YBJ [17], HAWC [4, 18], and GRAPES-3 [19], while IceCube [5] covers the south. Many mechanisms have been proposed to explain the medium-scale structures, including the effect of the heliosphere, non-uniform pitch–angle diffusion, non-diffusive galactic cosmic ray transport, small-scale anisotropies induced by magnetic turbulence, and exotic scenarios, however, the origin of medium-scale anisotropies remains debated [20].

In this work, we present measurements of medium-scale anisotropies above 10 TeV using data collected by the LHAASO-KM2A experiment and investigate their energy-dependent evolutions.

2. LHAASO Experiment

The Large High Altitude Air Shower Observatory (LHAASO), situated at an altitude of 4,410 meters in Daocheng, China (100.01°E, 29.35°N), is a hybrid cosmic-ray detection facility that began full operation in 2021. It integrates three sub-arrays: a 1.3 km^2 surface array (KM2A) comprising 5,195 electromagnetic detectors (EDs) and 1,188 muon detectors (MDs); a 78,000 m^2 water Cherenkov detector array (WCDA) organized into three water pools; and 18 wide field-of-view air Cherenkov/fluorescence telescopes (WFCTA) for atmospheric shower imaging. Following its transition to full-array operation on July 20, 2021, KM2A has continuously collected scientific data.

3. Data Analysis

This study utilizes the complete three-year dataset from KM2A, spanning July 20, 2021, to July 19, 2024, to analyze medium-scale structures of cosmic rays. To ensure the reliability of our analysis, the events in our analysis are selected following the criteria: the reconstructed zenith angle is smaller than 40°; the number of EDs used for reconstruction should be equal to or larger than 20; and the reconstructed shower core is located inside the array.

The energy of cosmic ray events is reconstructed employing a combination of the number of electromagnetic particles collected by EDs and muons recorded by MDs, which has been applied to measurements of cosmic ray spectrum beyond 300 TeV [21], and additional correction is used to flatten the energy distribution along the zenith.

To estimate the background maps of cosmic rays, the minimum chi-square method is employed to compute the relative intensity of arrival directions [22], which has been used in other ground-based experiments [1, 3, 23]. The estimated intensity $I(\alpha, \delta)$ comprises all angular scale structures,

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and what we focus on are those with angular size $\pi/\ell \leq 60°$, i.e., $\ell \geq 3$. Because the larger-scale structures are prominent, to reveal the medium-scale anisotropy, the lower multipoles should be subtracted. Here, the intensity $\delta I(\alpha,\delta) = I(\alpha,\delta) - 1$ is expanded in terms of a real spherical harmonic basis[4, 5], i.e. $\delta I(\alpha,\delta) = \delta I(\alpha,\delta)_{\ell\leq 2} + \delta I(\alpha,\delta)_{\ell>3}$ and $\delta I(\alpha,\delta)_{\ell\leq 2}$ is expressed as

$$\begin{aligned}\delta I(\alpha,\delta)_{\ell\leq 2} = m_0 &+ p_y \cos\delta \sin\alpha + p_z \sin\delta + p_x \cos\delta \cos\alpha \\ &+ Q_1 \cos^2\delta \sin 2\alpha + Q_2 \sin 2\delta \sin\alpha \\ &+ \frac{1}{2} Q_3 (3\sin^2\delta - 1) \\ &+ Q_4 \sin 2\delta \cos\alpha + Q_5 \cos^2\delta \cos 2\alpha,\end{aligned} \tag{1}$$

where m_0 is the quantity of monopole, and the values of (p_x, p_y, p_z) are the components of dipole moment, and the quantities of $(Q_1, Q_2, Q_3, Q_4, Q_5)$ are the components of quadrupole moment. The medium-scale and smaller-scale anisotropies are described by

$$I(\alpha,\delta)_{\ell\geq 3} = I(\alpha,\delta) - \delta I(\alpha,\delta)_{\ell\leq 2}, \tag{2}$$

where $\delta I(\alpha,\delta)_{\ell\leq 2}$ is obtained by fitting with Equation 2 to the data of $I(\alpha,\delta)$, and the free parameters are coefficients of multipoles, i.e. $(m_0, p_x, p_y, p_z, Q_1, Q_2, Q_3, Q_4, Q_5)$.

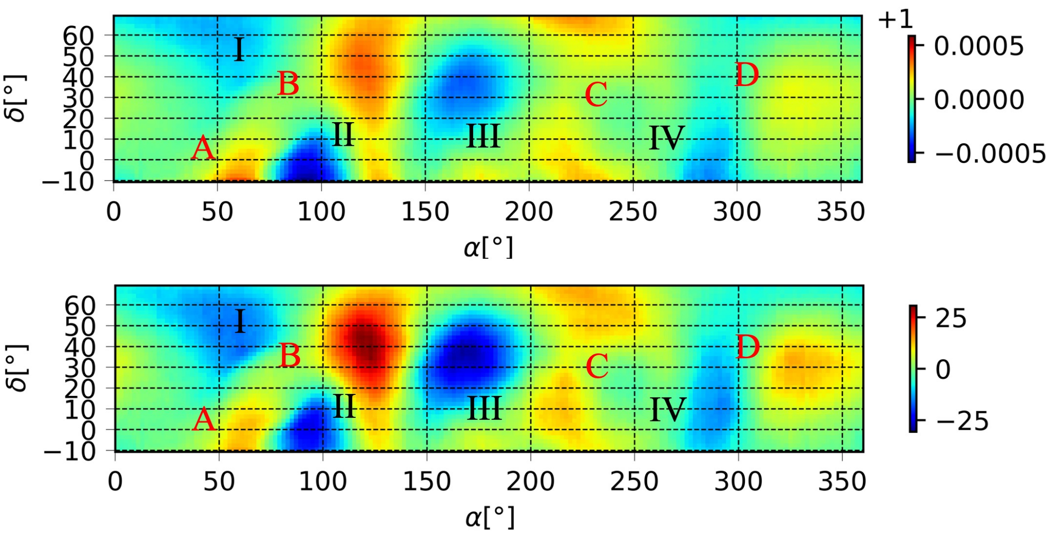

Figure 1: Sky maps of the significance of medium-scale structures in the celestial coordinates above 10 TeV. The map is smoothed with a top hat function with a radius of 18°. There are four excess regions labeled with A, B, C, and D, and four deficit regions denoted by I, II, III, and IV.

4. Results

The map of relative intensity (upper) and significance (lower) of the medium-scale anisotropies above 10 TeV (median energy is about 35 TeV) is shown in Figure 1. Four excess spots labeled as Region A, B, C, and D, and four deficit regions denoted as I, II, III, and IV, are detected by KM2A.

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Among these hot spots, Region A, B, and C have been reported by previous experiments [4, 16–19], while Region D is observed by KM2A for the first time. The sky maps for each energy bin are presented in Figure 2, from which we capture that the morphology of excess hot spots is energy dependent, especially Region D, i.e., Region D moves toward east when increasing energy.

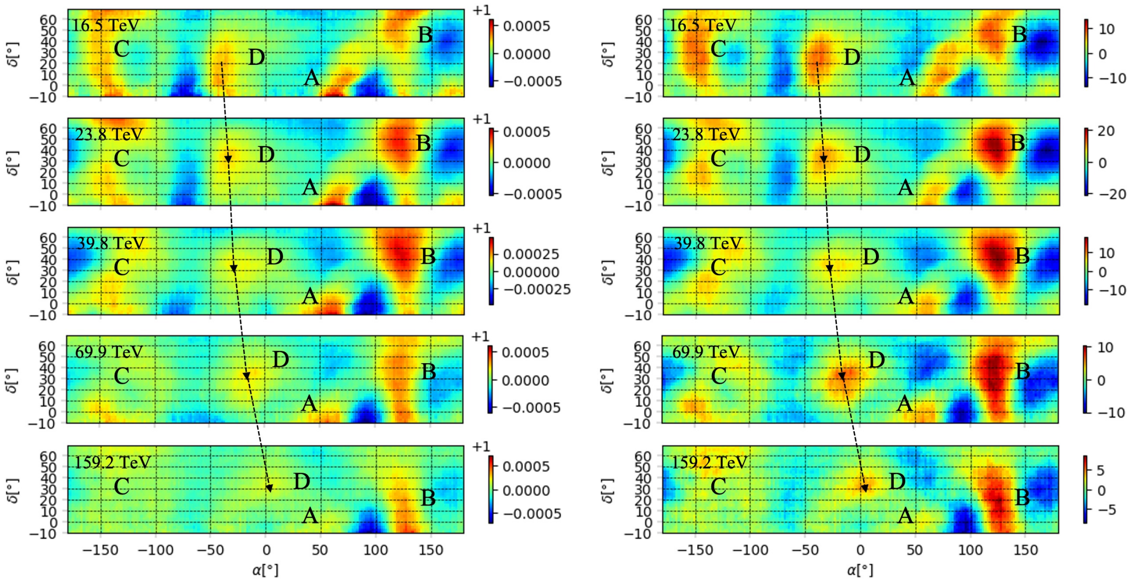

Figure 2: Sky Maps of relative intensity and significance of medium-scale structures of cosmic rays in the celestial coordinates, and to more clearly see the energy evolution of Region D, the maps have been rotated by 180° compared to Figure 1. The maps have been smoothed with an 18° top-hat smooth.

To determine the positions of medium-scale structures, a Gaussian distribution is employed to describe the relative intensity. And to describe the significance level of the movements of medium-scale structures, we compare the chi-square of fitting with 0th order (y=C, hereafter, y stands for right ascension or declination) polynomial and 1st order polynomial (y=alogE+b), the test statistic can be estimated by

$$TS = \Delta\chi^2 = \chi_0^2 - \chi_1^2, \tag{3}$$

where χ_0^2 is fitting from 0th order polynomial, while χ_1^2 obtained with 1st order polynomial. The significance is estimated by $\sqrt{TS}$. We find that the declination of Region B and the right ascension of Region D are highly dependent on energy, and the fitting plots are shown in Figure 3. For Region B, χ_0^2 = 151.1, χ_1^2 = 11.5, and for Region D, χ_0^2 = 259.8, χ_1^2 = 3.1., therefore, the significance for the movement of the declination of Region B is about 11.8 σ, and the significance for the right ascension of Region D is about 16.0 σ. The significance of other regions is below the 5 σ detection threshold, and more data is required.

The energy-dependent evolution of medium-scale anisotropy morphology, as demonstrated by [24], arises from the turbulent Galactic magnetic field structure within the cosmic rays' scattering length from Earth. Our discovery of energy-dependent shifting of Regions B and D provides important and strong new constraints on the structure of local magnetic fields.

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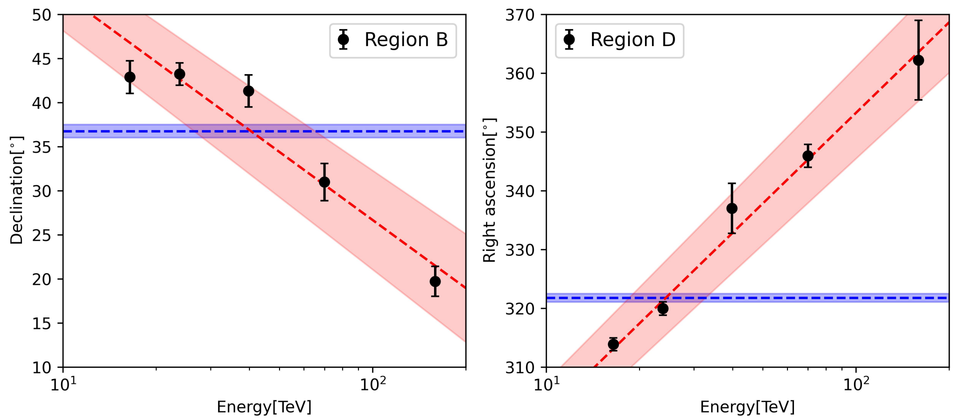

Figure 3: The energy-dependent positions of Region B and Region D. The dashed lines are the best fits, while the shaded regions are the 68% C.L. intervals.

5. Conclusion

In this work, using LHAASO-KM2A full-array data of cosmic rays accumulated from July 20, 2021, to July 19, 2024, we report the measurements of the medium-scale anisotropies of very high-energy cosmic rays at energies from 10 TeV to above 100 TeV. An iterative method is utilized to estimate the reference maps of isotropic backgrounds, whereafter, the relative intensity is expanded with a set of spherical harmonic bases, and the lower multipoles with $\ell \leq 2$ are subtracted to derive the sky maps of medium-scale structures. We have observed four excess regions and four deficit regions, among which Region B and Region D show strong evidence of energy-dependent shifting, specifically, Region B moves toward the south, and Region D shifts to the east with increasing energy. The energy-dependent movements of medium-scale structures are reported for the first time, which would have strong constraints on the structures of turbulence and propagation of cosmic rays.

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