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The large-scale anisotropy of cosmic rays based on LHAASO-KM2A

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The large-scale anisotropy (LSA) of cosmic rays, which exhibits a complex evolution with energy, is an important probe to unraveling the mystery of the origin and propagation of cosmic rays. However, the previous observation for LSA have limited accuracy at high energies (above hundred TeV), and the measurements focus on the mixed-composition of cosmic rays. The 5216 electromagnetic particle detectors and 1188 muon detectors in the square kilometer array (KM2A) of LHAASO allows the ground-base array to identify the primary composition of cosmic rays with unprecedented sensitivity by measuring the muon component in the air shower. In this work, we present the LSA of all particle cosmic rays from tens TeV to about 10 PeV obtained from three years' data of KM2A. A preliminary study for the light-composition (protons and helium) of LSA were also introduced. These results are expected to provide important information for the physical interpretation of LSA, and consequently the propagation of cosmic rays.

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1. Introduction

The large-scale anisotropy (LSA) of cosmic rays is an important way to understand the origin and propagation of cosmic rays. The LSA has been observed by many experiments across a large energy range, from sub-TeV to dozens EeV. The characteristics of LSA, which evolved with energy, provide hints about its origins, such as the diffuse of cosmic rays propagation, modulation from magnetic fields and distribution of cosmic ray sources and so on. Measuring LSA around the PeV energy range (i.e.,"knee") and its dependence on cosmic ray components are significant to reveal the origins of LSA.

The previous measurements at the TeV range have more results and with higher precision. As the flux of cosmic rays decrease rapidly with energy, it becomes challenging to measure LSA above around the "Knee" range. Until now, LSA in the PeV energy and more high energy were only observed by a few experiments and with larger uncertainties. Furthermore, identifying the primary component of cosmic rays was difficult in early ground-based experiments, such made the measurement for component anisotropy more difficult.

Large High Altitude Air Shower Observatory (LHAASO, located at 4410m a.s.l.) is a new generation hybrid array, consisting the Water Cherenkov Detector Array (WCDA), one square kilometer array (KM2A) and Wide Field Chenrenkov Telescope Array (WFCTA). KM2A consists of 5216 Electromagnetic particle Detectors (ED) and 1188 Muon Detectors (MD). The high altitude and large area of KM2A enable it to accurately measure the PeV cosmic rays and detect cosmic rays across a wide energy range from tens TeV to 100 PeV. The MD array can provide muon component which can be used to identify the primary cosmic ray. With these advantages, KM2A is suitable for more detailed study of cosmic ray anisotropy.

2. Data and simulation

Three year's data collected by KM2A from Jan. 2020 to Dec. 2022 was selected for this work. The events were selected with the followed criteria. The number of triggered ED after noise filter is not less than 20, the reconstructed shower core located in the array, the zenith angle little than 40 degrees, the number of electromagnetic partciles is not less than 20 ($N_e \geq 20$), the number of muon should be $N_\mu \geq 10$, and the reconstructed energy above 30 TeV ($log(E_{rec}/GeV) > 4.5$). After these selection, there are about 2.9×10^{10} events survived, and figure 1 shows the daily events number from 2020 to 2022, which contain three epochs correspond to 1/2, 3/4 and full array respectively.

The extensive air shower is simulated with COSRKA7.74 [1] and we selected the QGSJETII-04 [2] for the hadronic interaction at high energy and the FLUKA [3] for low energy. Five groups(P, He, CNO, MgAlSi, Fe) showers were sampled from 10TeV to 10 PeV. The composition and energy spectrum of simulated events adopt to model of [4]. The GENT4-based detector simulation code G4KM2A [5] was used to determine the response of 1/2, 3/4 and full KM2A. A combined parameter $N_{e,\mu}$, which consist of the number of electromagnetic particles N_e and the muons N_μ, was used to estimate the energy [6].

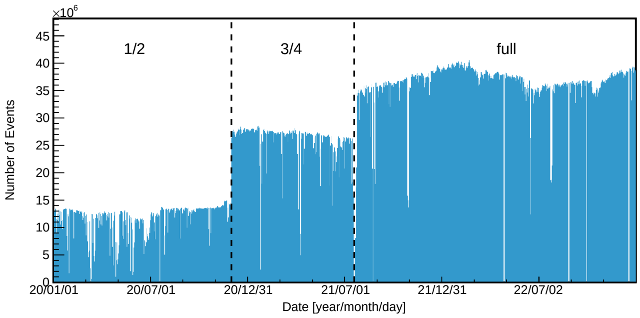
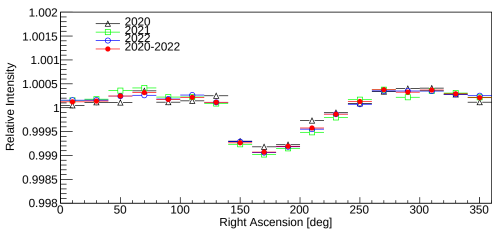


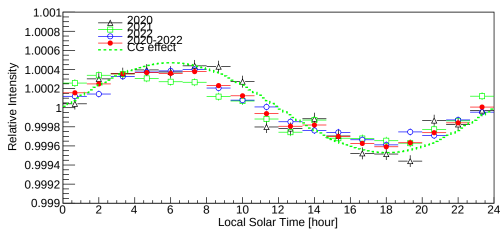
Figure 1: The daily distribution of the selected events from 2020/01/01 to 2022/12/31.

3. LSA of all particles

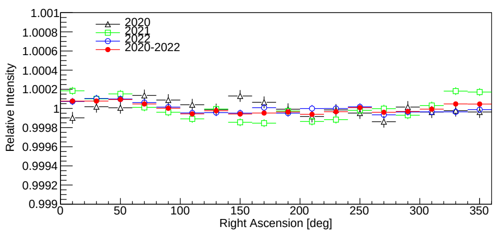
The time-stability was studied by observe the LSA during each year form 2020 to 2022. Figure 2 displayed the LSA in different epochs. Plot (a) and (b) shows the sidereal anisotropy and solar anisotropy separatly. Two spurious time, anti-sidereal and ext-sidereal time, are plot in (c) and (d) separatly. The magnitude in spurious time scales are usually considered as the systematic uncertainty. The systematic errors are observed on the order of $\sim 10^{-4}$. Considering the errors, the LSA both in sidereal and solar time are stable during these years. The dotted green line in plot (b) represent the expected anisotropy, which due to the Compton-Getting effect. The observed dipole anisotropies in the solar time consist with the expected Compton-Getting effect.



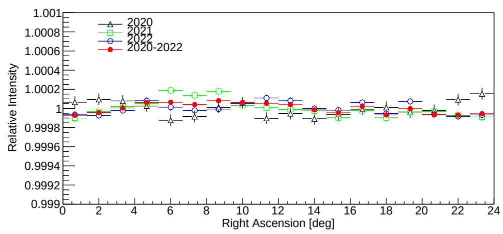
(a) sidereal time



(b) solar time



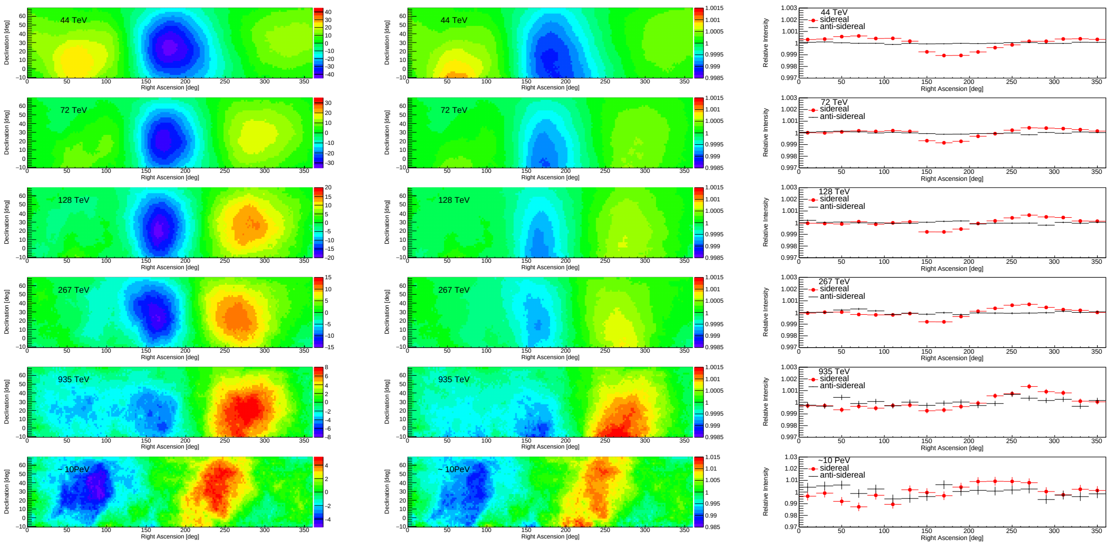
(c) anti-sidereal time



(d) ext-sidereal time

Figure 2: The time stability of LSA in four time scales.

To study the evolution of LSA with energy, the events was divide into six intervals according the reconstructed energy. The median energies of six data samples are 44 TeV, 72 TeV, 128 TeV, 267 TeV, 935 TeV and ≥10 PeV respectively. The events of last data sample was selected with the reconstructed energy above 10 PeV. Figure 3 shows the LSA from 44 TeV to 10 PeV. Column (a) and (b) shows the sky maps of significance and relative intensity of LSA. Column (c) plot the relative intensity of cosmic rays which project on the direction of right ascension. The red dots represent the sidereal time scale. And the black lines represent the residuals in anti-sidereal time, which are used to estimate the systematic error. Figure 3 have exhibited a significant evolution of LSA with energy. The so called "Tail-in" vanished since ~70 TeV, another "excess" around 250 ~ 300°$R.A.$ started appears. The "loss-cone" vanished at more high energy. The strength of the "excess" becomes stronger as the energy increases.Around 10 PeV,about 1.32 million events were selected and the LSA with a significance of about 5σ. At such high energy, the direction of the "excess" shifted from 250 ~ 300°$R.A.$ to 200 ~ 270°$R.A$, i.e. the excess have more large deviation from the direction of galactic center.



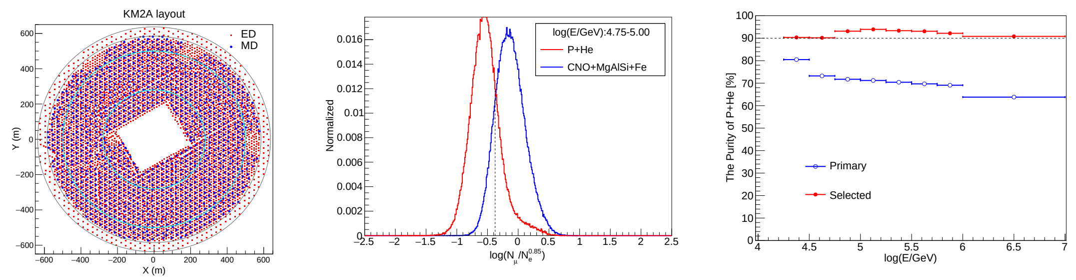
(a) significance sky maps (b) relative intensity sky maps (c) relative intensity projection on right ascension

Figure 3: The evolution of LSA with energy observed by LHAASO-KM2A.

4. Preliminary study for the Light-component LSA

Beside the all particle cosmic rays, we also attemped to study the LSA of divided composition. For the ground based experment, it is difficult to pick out the individual components. In this work, we use the muon component to select light-composition data sample. The data only from the full KM2A in one year was used. Based on the all-particle conditions, the events must located in the centre range of the array with the distance of the reconstructed shower core from the array center in the range of 280 m to 500 m, as figure 4 (a) shown. A parameter defined as $C_{e,\mu} = log\frac{N_\mu}{N_e^{0.85}}$ was used to identify the composition of cosmic rays. Plot (b) shows that the light composition have small value of $C_{e,\mu}$ than heavy composition. A critical value C_0 was determined (dotted line) to distinguish the light component with $C_{e,\mu} < C_0$. Plot (c) shows the $P + He$ purity of the light-composition of data samples. This composition identification method can selected a light-composition data sample with purity above 90% in each energy interval.

The evolution of light-composition LSA with energy was also studied. Figure 5 shows the LSA of light-composition ($\%90purity$) with median energy of 27 TeV, 40 TeV, 63 TeV, 114 TeV, 212 TeV, 378 TeV, 677 TeV and 1452 TeV seperately. The sky maps of significance (column (a)) and relative intensity (column (b)) show that the features of LSA have no obvious difference compared with all particles. Column (c) shows the sidereal anisotropy and the residuals in anti-sidereal time. In short, the results of light component are very preliminary and with large uncertainties, we should do more studies for the light component LSA measurement.



(a) Core selection (b) identify parameter (c) purity of light component

Figure 4: The data sample selection for the light component.

5. Conclusion

LHAASO-KM2A have observed the large-scale anisotropy of all-particle cosmic rays from 2020 to 2022. The LSA are stable during this three years considering the systematic uncertainties. A dipole anisotropy in solar time was observed and it approximate to the expected Compton-Getting effect. The evolution of LSA from 44 TeV to 10 PeV were measured, and the anisotropy at 10 PeV reached 5σ significance. Furthermore, a preliminary result for the light component, with about 90% purty, of cosmic rays was also report here. The tendency of the evolution with energy is similar with the all particles' result. However the very preliminary measurement still have very large uncertainty, and more studies need to done. As LHAASO has already started full array operation, it will measure the anisotropy from sub-PeV up to tens of PeV anisotropy more accurately with the data accumulate.

Acknowledgments

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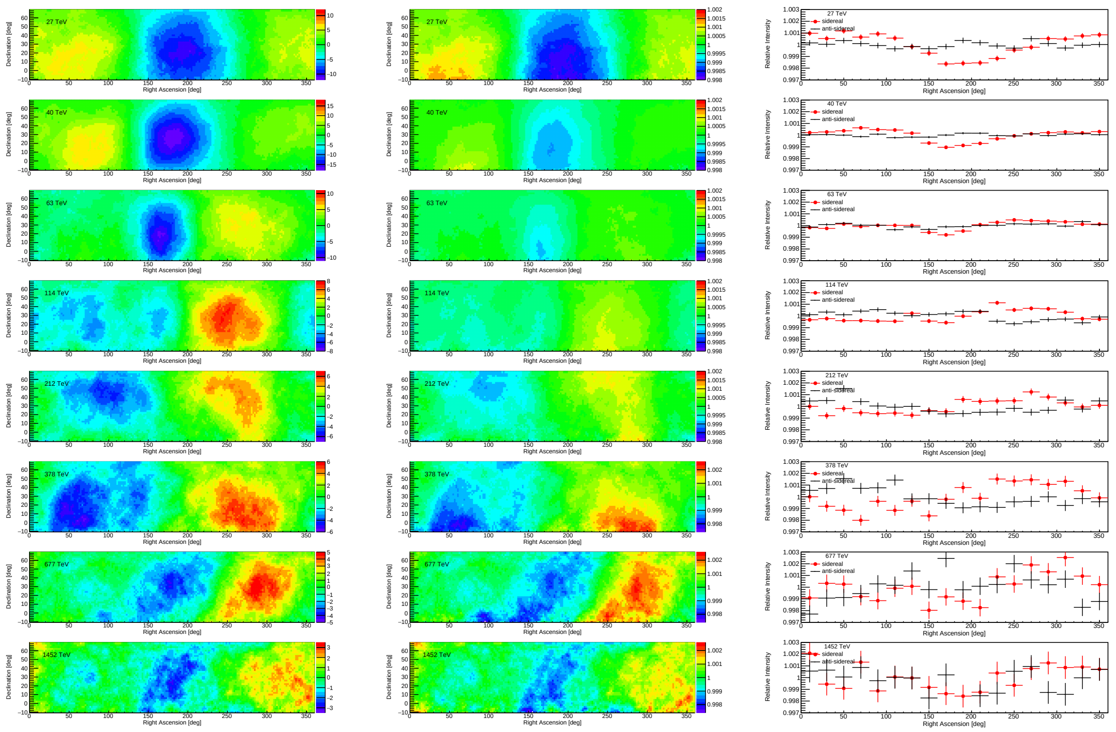

(a) significance sky maps (b) relative intensity sky maps (c) relative intensity projection on right ascension

Figure 5: The LSA of light component.

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