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Observations of extended very-high-energy halos around Geminga and Monogem with the LHAASO-KM2A

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Gamma-ray halos around pulsars are an effective probe of particle propagation in the interstellar medium. Two halos named Geminga and Monogem are observed by the KM2A, one of the sub arrays of the Large High Altitude Air Shower Observatory (LHAASO). The significance of Geminga(Monogem) is 11 σ (7 σ) at the energy range from 25 TeV to 63 TeV. In the future, more statistics will allow us to investigate the energy-dependent morphologies.

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1. Introduction

The origin and propagation of cosmic rays (CRs) are very important questions in physics and astrophysics. The conventional model suggests that CRs, after being accelerated by extreme astronomical objects, propagate diffusively in the random magnetic field of the Milky Way, interact with matter and field during the propagation and produce secondary particles [2]. The diffusion coefficient is the most important parameter to characterize the propagation of CRs. It is also a very important measure of the property of the interstellar medium. Usually one can use the secondary-to-primary ratio of CR nuclei, such as the Boron-to-Carbon ratio, to measure the diffusion coefficient.

Observations of ultra-high-energy (UHE) gamma rays are another very important method to probe the origin and propagation of CRs. In 2017, the High Altitude Water Cherenkov observatory (HAWC) discovered extended very-high-energy (VHE) gamma-ray halos around two middle-aged pulsars, Geminga with an age of 342 kyr and Monogem with an age of 110 kyr, which are expected to be produced by UHE electrons and positrons accelerated by the pulsars and then radiate through inverse Compton scattering off the interstellar radiation field [1]. Through measuring the morphologies of the extended emission, the HAWC collaboration concluded that charged particles diffuse extremely slowly around those pulsars. The diffusion coefficient inferred from the HAWC gamma-ray observations is smaller by two orders of magnitude than that derived from the CR Boron-to-Carbon ratio.

However, the energy-dependence of the diffusion coefficient around Geminga remains a puzzle, which is a crucial key to investigate the properties of magnetic field turbulence. Because the diffusion coefficient is determined by the average strength of the magnetic field B and its degree of turbulence δB on length scales comparable to the gyration radius. Traditionally, the diffusion coefficient grows with energy according to a power law, the exponent of which depends on the turbulent nature of the magnetic field. In Kolmogorov's theory, the exponent equals 1/3 power[4]; in Kraichnan's hypothesis, the exponent is 1/2 power[5]; in the Bohm Limit case, the exponent equals 1 power.

LHAASO-KM2A is the most sensitive observatory for gamma rays above 20 TeV and is thus a very powerful probe of the UHE gamma-ray emitter. Compared with HAWC, LHAASO is superior in the energy band coverage, energy resolution, and sensitivity. LHAASO has a large field of view and is therefore very appropriate for the extended source observations. LHAASO is unique to reveal the energy-dependent morphologies of the emission, and can provide very important information on the energy-dependence of the diffusion coefficient.

2. LHAASO-KM2A

The kilometer square array(KM2A) is an important part of LHAASO that is located at Haizi Mountain, Daocheng, Sichuan province, China. It is currently the most sensitive detector above 20 TeV and the half array of LHAASO-KM2A (1/2KM2A) has been continuously observing VHE gamma rays since 2019. As shown in the figure 1, 1/2KM2A contains 2365 scintillator detectors (Electromagnetic particle Detector, ED) and 578 muon detectors (MD), where the EDs are used to reconstruct the direction of the event and the MDs mainly detect the Muon component of secondary particles, which are used to distinguish between gamma and proton, since the Muons produced by gamma rays is poorer than those from protons. The rejection power of cosmic ray induced showers is better than 4×10^3 at energies above 100TeV. The 1/2KM2A data collected from 27th December,2019 to 7th December, 2020 is used in this analysis.

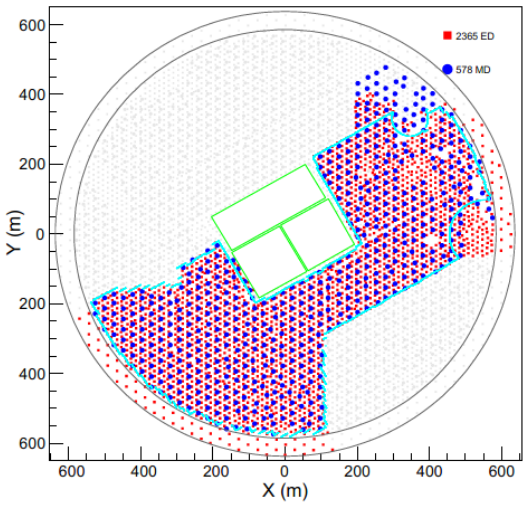

Figure 1: Layout of the whole LHAASO-KM2A.The red circles and blue squares indicate the EDs and MDs in operation, respectively. The light gray markers indicate the prospective EDs and MDs.

The simulation sample used in this study is the same as in the Crab analysis, and the simulated samples of both sources were produced by reweighting the event according to the source tracks. Its reliability has been verified in the paper [3].

3. method

To estimate the background mainly contributed from cosmic rays, the equi-zenith angle method is adopted. This method assumes that detector effectiveness is the same throughout zenith belts and the background of one grid can be valued as the average of the sideband. In addition, we mask the Galactic Plane and other known TeV-source regions, in case that the $gamma$-ray sources are at the sideband and overestimate the background. The mask region for the Geminga and Monogem is two circles with a radius of 15 degrees due to their large extension.

The maximum likelihood ratio is constructed by comparing the diffusion model with the none source model to analyze the morphologies of both sources. The diffusion template read as formula 1, where A is the normalization constant indicating the signal intensity, θ_d is the diffusion angle,$\theta_d = \frac{180^\circ}{\pi} \cdot \frac{2\sqrt{D(E_e)t_E}}{r}$, and t_E is the cooling time of the electron, r is the source distance. This template describes gamma rays produced by continuously injecting electrons via Inverse Compton(IC) progress. To avoid the detector impact on the θ_d, the convolution function of diffusion template and angular resolution is used to fit experimental data. Due to the similarity of both sources in age, we presume that the diffusion property is the same for both sources. To avoid contamination from other known sources, we deducted a circular area of 2 degrees around each source, as shown in Fig. 2.

$$f(\theta) = \frac{A}{\theta_d(\theta + 0.085\theta_d)} \exp[-1.54(\theta/\theta_d)^{1.52}], \tag{1}$$

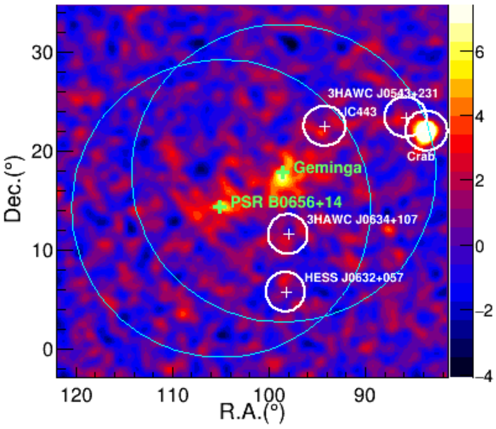

Figure 2: The figure shows the significance of Geminga in the range of 15-25 TeV. The blue circle with a radius of 15 degrees indicates the region of intrerest. the white circle with a radius of two degrees in the figure indicates the deducted region of known intrahelial sources.

4. Results and discussion

The clear excesses around Geminga and Monogem in different energy ranges are observed in Fig.3. The two sources are marked as full crosses and the statistical significances of Geminga(Monogem) are $8\sigma(7\sigma)$ at 10-25, $11\sigma(7\sigma)$ at 25-63 TeV. This map is obtained by the likelihood test between the two-dimensional Gaussian model and the background-only model, the Gaussian sigma values are 0.5°, 0.26° and 0.25°, which corresponds to the PSF of KM2A in each energy range.

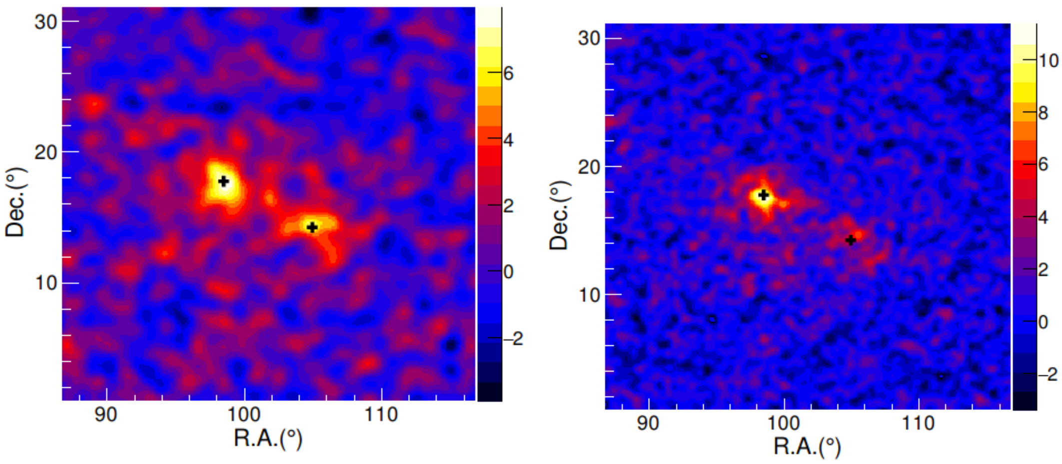

Figure 3: Significance maps of Geminga and Monogem at different energies(left: 15 TeV<E<25 TeV Right:25 TeV<E<63 TeV). The two black crosses denote the Geminga Pulsar(upper left) and the Monogem Pulsar(bottom right) respectively.

The morphology analysis is going on and more data by KM2A in the future will allow to investigate the energy-dependence of the morphology.

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