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Updated analysis of the brightest UHE Gamma-ray Source LHAASO J1825-1326

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Searching for ultra-high energy (PeV) cosmic ray accelerating source is the core problem in the study of cosmic ray origin. One of the most direct methods is to look for the ultra-high energy gamma-ray radiation generated by the interaction between cosmic rays and interstellar gas near the accelerator. Twelve ultra-high energy gamma ray sources have been observed on the galactic disk by the Large High Altitude Air Shower Observatory (LHAASO). Here, we report the result for LHAASO J1825-1326 region using the Water Cherencov detector array (WCDA) and kilometer array (KM2A) data. The γ-ray emission above 1 TeV observed by LHAASO from the region of LHAASO J1825-1326 is well described by four components including galactic diffuse emission, 1LHAASO J1825-1418 and 1LHAASO J1825-1256u, the likely counterparts to known γ-ray sources, HAWC J1825-138 and HAWC J1826-128, respectively, and LHAASO J1825-1256u in the middle. At present, the origin and radiation mechanism of 1LHAASO J1825-1337u can not be fully confirmed. While CRs accelerated to energies of several PeV colliding with the ambient gas likely produce the observed radiation.

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1. Introduction

The mechanisms of the origin, acceleration, and propagation of cosmic rays remain an unsolved mystery in the domain of cosmic ray research. The accurate measurement of the "knee" energy spectra of different cosmic mass compositions is important for elucidating the origin of cosmic rays.

The Large High Altitude Air Shower Observatory (LHAASO) is located at Haizi Mountain, Daocheng, Sichuan, China, at an altitude of approximately 4410 m. The LHAASO consists of three main detector arrays: the 1.3-square-kilometer array (KM2A) of electromagnetic particle and muon detectors, water Cherenkov detector array (WCDA) with a total active area of 78,000 m^2, and wide field-of-view (FoV) Cherenkov telescope array (WFCTA) consisting of 18 wide FoV imaging atmospheric Cherenkov telescopes.

Using 508 days of data collected by the Water Cherenkov Detector Array (WCDA) from March 2021 to September 2022 and 933 days (corresponding to 730 days of complete KM2A detector) of data recorded by the 1 km2 array (KM2A) from January 2020 to September 2022. This catalog represents the most sensitive gamma-ray survey of the sky covering the declination from -20° to 80°. In total, the catalog contains 90 sources with extended size smaller than 2° and with significance of detection at > 5σ[1]. Among those high energy galactic gamma-ray sources, the most bright source 1LHAASO J1825-1337u and 1LHAASO J1825-1256u stands out with the emission above 100 TeV.

2. Analysis of the region of LHAASO J1825-1326

In order to assess the significance of the detected sources we used the likelihood ratio test statistic (TS) defined as:

$$TS = 2(\frac{L_{alt}}{L_{null}}) \tag{1}$$

where L_{alt} is the maximum likelihood of the alternative hypothesis and L_{null} is the likelihood of the null hypothesis. The region of interest used in the analysis is $16° < l < 20°$ and $-3° < b < 3°$ around the position of LHAASO J1825-1326.

From this study we found the LHAASO J1825-1326 region can be well described by one extended Gaussian-shaped γ-ray source (The white circle in the Fig 1, 1LHAASO J1825-1418) plus two point source (The white stars) on top of the galactic diffuse emission (GDE). The two point sources, 1LHAASO J1825-1337u and 1LHAASO J1825-1256u, are likely to have known γ-ray counterparts which are HAWC J1825-134 and HAWC J1826-128, respectively. The positions of the pulsar PSR J1826-1334 might be associated with 1LHAASO J1825–1418 and PSR J1826–1256 associated with 1LHAASO J1826–1256u are also shown in Fig 1.

To confirm the source extension in this region, a likelihood ratio test is performed between the model using three point sources and a two point source with one extend source model. According to Wilk's theorem, for nested models by assuming the two-source model is true, the TS is distributed as χ^2 distribution. The test result shows that the three-source model, which consists of two point sources and an extended source, is favored by ΔTS = 33. 1LHAASO J1825-1337u is associcated

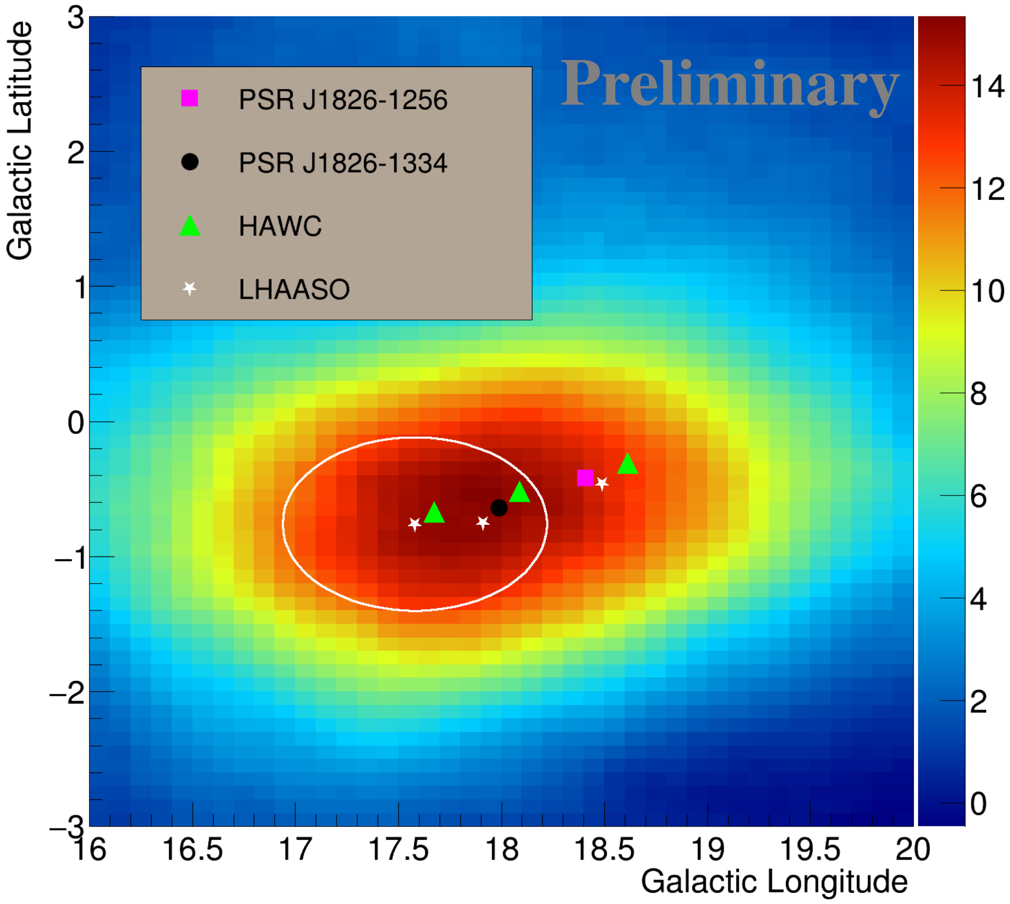

Figure 1: Significance map of LHAASO J1825-1326 region. From left to right, the white stars (green triangles) represent the position of 1LHAASO J1825-1418 (HAWC J1825-138), 1LHAASO J1825-1337u (HAWC J1825-134), and LHAASO J1825-1256u (HAWC J1826-128).

with HAWC J1825-134. As shown in the Fig.2, the spectral energy distribution of 1LHAASO J1825-1337u extended beyond 200 TeV no longer follows the simple power-law spectrum as described in [2]. A detailed study of the LHAASO J1825–1326 region will be made in forthcoming publication.

3. Morphological analysis

Analysis was conducted in six energy bands, in which the nebula size of can be clearly seen to decrease with increasing energy, as shown in Fig.3. This is supporting evidence that the emission is attributable to PSR J1826-1334, and it provides some indication that the electron population cools over time as the particles are transported away from the pulsar. Located at R.A.: 18h26m13.06s, Dec: 13°34′48.1", it is a young pulsar (characteristic spin-down age τ = 2.14 × 10^4 yr) with a spin-down power of $\dot{E}$ = 2.8 × 10^{36} erg s^{-1} and a period of P = 0.1015 s, situated at a distance of approximately 4 kpc[3, 4]. The nebula morphology is highly asymmetric and offset from the

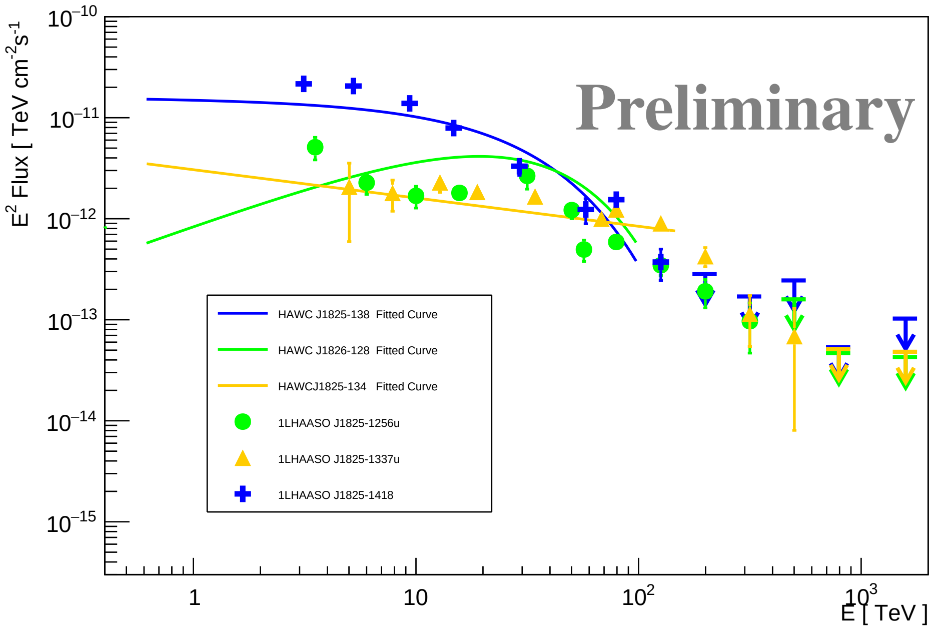

Figure 2: γ-ray spectral energy distribution for the sources in the region of interest around LHAASO J1825-1326.

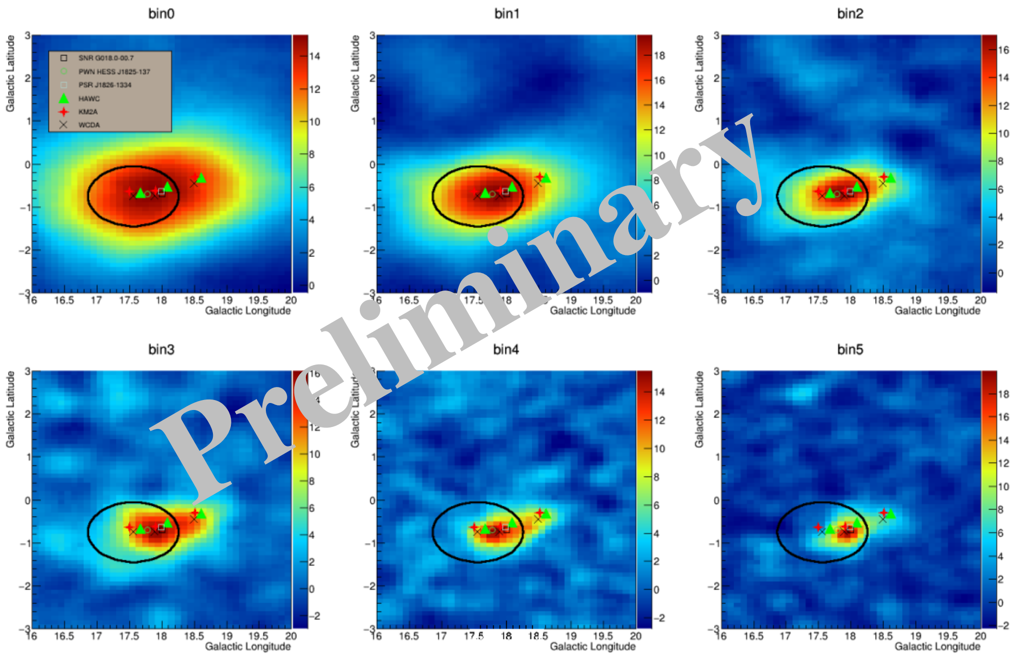

Figure 3: Significance map of of the LHAASO J1825-1326 region in six different energy bands. The size of the nebula is clearly much reduced at high energies. The positions of the pulsars PSR J1826-1334 might be associated with 1LHAASO J1825-1418 and PSR J1826–1256 associated with 1LHAASO J1825-1256u are also shown.

pulsar position. The possible explanation could be that in the past the external part of the supernova shell interacted with the nearby molecular cloud, leading to a relatively fast formation of a reverse shock on the northern side of the nebula, which would prevent the outflow of radiating particles near the shock front and the recoil of this reverse shock forced the nebula to expand more towards the southern side, but with only minor extension towards the north. [5]. The changing extent with energy is apparent in the significance maps in different energy bands shown in Fig 3.

4. Conclusion

The studies of LHAASO J1825-1326 region find the γ-ray emission of 1LHAASO J1825-1337u extended beyond 100 TeV. LHAASO's flux point beyond 200 TeV no longer follows the simple power-law spectrum. And the energy-dependent morphology of large extended source 1LHAASO J1825-1418 can be clearly seen to decrease with increasing energy, it might be coincident with the pulsar PSR J1826-1334 location. The future LHAASO analysis will help to solve the puzzles in the LHAASO J1825-1326 region.

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