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Observation of TeV gamma ray emissions from 12 UHE gamma ray Galactic sources with the LHAASO-WCDA

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The Large High Altitude Air Shower Observatory (LHAASO) reported detection of 12 ultrahigh-energy (>100TeV) gamma ray sources with a statistical significance greater than seven standard deviation by the kilometer aaray (KM2A). In total, more than 530 photons are recorded from these sources at energies above 100 TeV with the highest photon energy extending up to 1.4PeV. We here report the observations of LHAASO Water Cherenkov Detector Array (WCDA) with 508 day live time on these sources. Energy spectra and morphologies of those sources are measured in the energy range of 2-20 TeV. Combing KM2A data, a wide range of energy spectral fitting of these sources is provided.

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1. Introduction

Recently, LHAASO reported the discovery of 12 ultra-high-energy cosmic ray sources with energies greater than 100 TeV in the Milky Way[1]. Although there are several potential counterparts nearby, including pulsar wind nebulae, supernova remnants, and star-forming regions, the origin of these extreme accelerators is still unknown. However, this opens a window to study the origin of cosmic rays through high-energy gamma-ray sources.

Measurements of multi-band broad energy spectra will provide more help in understanding the properties of these high-energy sources. Therefor,We used the WCDA (Water Cherenkov Detector Array) sub-array of LHAASO (Large High Altitude Air Shower Observatory) to observe gamma radiation in the 2-20 TeV range in these regions and obtained the energy spectra and shapes of these sources.

The paper is organized as follows: In the first section, we provide an overview of the observation capabilities and characteristics of the WCDA array. The second section details the analysis method employed for the experimental data. Lastly, we present the results of our study on the measurement of the energy spectra and shapes of 12 ultra-high-energy gamma-ray sources within the energy range of 2-20 TeV.

2. Instrument and data set

The Water Cherenkov Detector Array(WCDA) detects showers in the primary energy range from 100 GeV to 20 TeV[2], and constitutes an important part of The Large High Altitude Air Shower Observatory (LHAASO) experiment, located on the Daocheng site, Sichuan province, P.R. China. WCDA is designed primarily for observing transient phenomena and discovering new sources, with wide field of view and all-weather operation. It is optimized for gamma-ray astronomy in the TeV regime. For the gamma ray source survey, the designed sensitivity is about 1% Crab Unit [3].

The data used in this study were obtained from the full-array operation of the WCDA from March 5,2021 to September 30, 2022, with a total exposure time of 508 day. The Gamma-Proton identification parameter named "pincness" [4] is cut to be less than 1.1, and zenith angle of shower is less than 50 degree for event selection. The data is divided into five energy segments based on the number of triggered detectors(nhit), and the ranges of each segment are 100-200, 200-300,300-500,500-800 and 800-2000. The medium energy of events with nhit greater than 100 is approximately 2 TeV, with a power-law spectrum index of -2.6.

3. Analysis method

Despite applying proton-gamma discrimination filtering, cosmic ray background still exists in the events from the source region. Thus, we utilized an All-Sky method called "direct integration" [5] to estimate the background. Due to the fact that almost all of our analyzed objects (as shown in Figure 1) are located in the Galactic plane (except for CRAB), the existence of a large number of sources makes the radiation signal very complex. The 3-dimensional likelihood fitting method is developed in this analysis. Data at different energy bands are fitted simultaneously by assuming a spatial template and an energy spectrum form for each source in the region. The point spread function (PSF) as a function of energy is convoluted with the spatial template. The detector responses as a function of energy and zenith are considered according to the detailed detector simulation. In this way, both morphological and spectral information are taken into consideration to account for contributions from individual sources.

The test statistic is used to evaluate the significance of a source and is defined as $TS = 2\log(L_{alt}/L_0)$, where L_{alt} represents the likelihood of the alternative hypothesis, and L_0 is the likelihood of the null hypothesis. According to Wilks' Theorem [6], TS follows a chi-square distribution with degrees of freedom equal to the difference in the number of free parameters between the two hypotheses.

The map of the TS values obtained in the 3D-likelihood fitting procedure is used to represent the morphology of the region of sources. Particularly in the analysis, a 2-dimensional Gaussian template with a spectral index of -2.6 in every pixel of the map is assumed. The spectrum index are chosen to present the most common situations for sources measured by the detector systems. In this way, the TS map of each source can be separated individually according to the best-fit model.

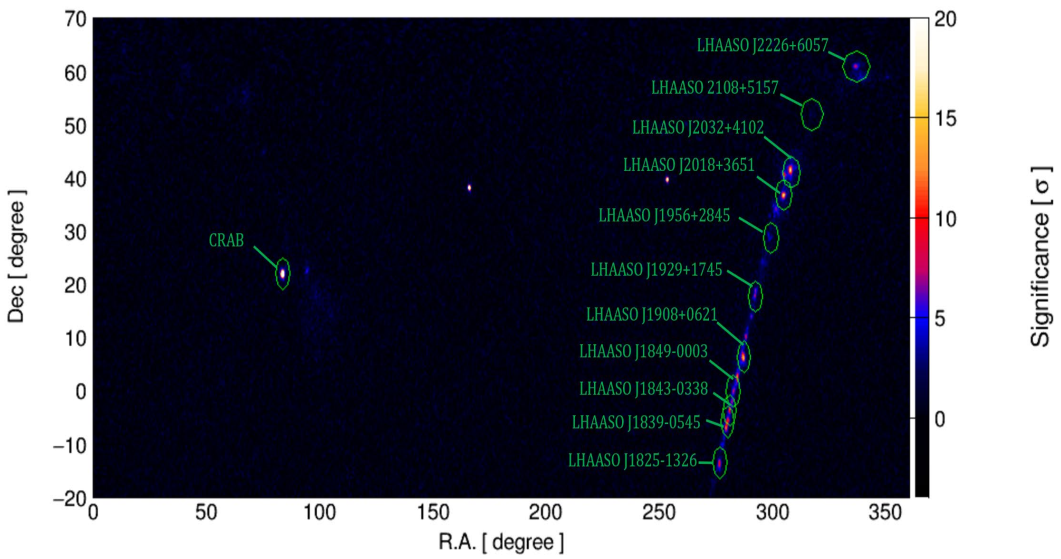

Figure 1: The distribution of 12 UHE sources on the celestial sphere.The green circles are circles with a radius of 3 degrees centered on each source,which the center and name of sources comes from the article [1]. They are set to display the distribution of these sources in the Milky Way, with a maximum significance set to 20.

4. Analysis result

4.1 CRAB Nebula

The Crab Nebula is the brightest TeV gamma-ray source in the sky which is used to calibrate and verificate the new TeV instruments. We first applied the analytical method and data mentioned above to obtain the energy spectrum of the standard candle Crab Nebula. The results are shown in

Figure 2. The fitted positional parameters were ra=83.62±0.01° and dec=22.01±0.01° . The energy spectrum model used was in the form of a logarithmic parabola $f(E) = \alpha(\frac{E}{E_0})^{-\beta - klog(E/E_0)}$, and the fitted parameters were $\alpha = (2.23 \pm 0.03) \times 10^{-9} TeV^{-1}m^{-2}s^{-1}$ at $E_0 = 7TeV$, $\beta = 2.79 \pm 0.02$ and $k = 0.06 \pm 0.01$ with $\chi^2/ndf = 0.39/2$ .The results were consistent with those previously reported[7], which also validated the reliability of our method and data.

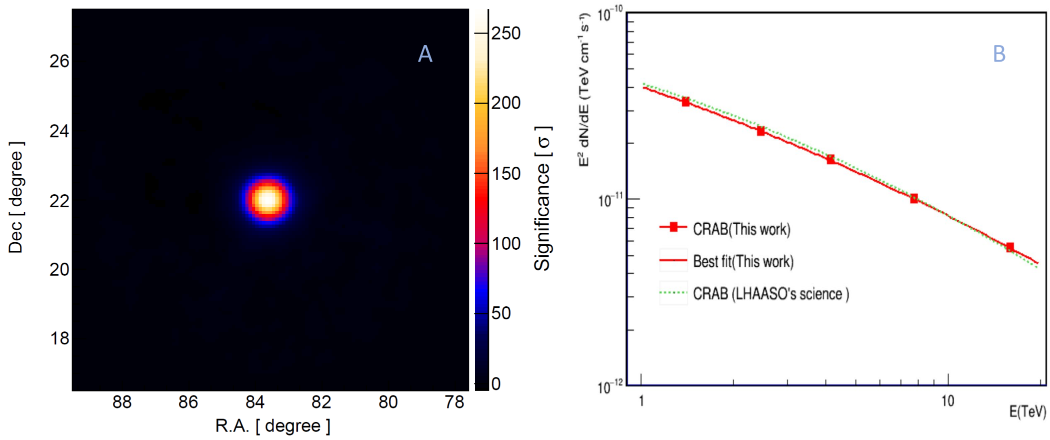

Figure 2: A: The significance of the CRAB Nebula excluding the neighboring TeV halo reported by HAWC.[8] B: The red boxes represent the experimentally observed points obtained from the fit, the red solid line is the best-fit model, and the green dashed line represents the results published by LHAASO in Science[7].The red boxes represent the experimentally observed points obtained from the fit, the red solid line is the best-fit model, and the green dashed line represents the results published by LHAASO in Nature. They achieved consistent results for CRAB spectrum measurement within a 5% error range.

4.2 The fitting result of 12 UHE sources

As shown in Figure 1, these sources are mostly located on the Galactic plane, and the signals of multiple sources within the region of interest (ROI) overlap with each other. We need to extract the sources of interest from this overlapping signal.

We modeled these sources using a two-dimensional Gaussian spatial model characterized by the sigma parameter to represent the source extension, and a two-parameter power-law function . We selected data within a certain angular distance range centered on each source, and applied the same 3D likelihood analysis framework using a stepwise approach to perform maximum likelihood fitting. The best-fit parameters for their spectral and morphological models are listed in Table 1. The extend of these sources is small and the largest one is only around 0.5 degrees,indicating that the radiation originates from a relatively compact region. The significance of all these source is larger than 5 times standard deviation, which could provides statistical support for the subsequent joint spectral analysis and also offers more constraints for determining the properties of these UHE sources.

$name$	$ra(deg)$	$dec(deg)$	$R_{40}(deg)$	$flux(10^{-9}TeV^{-1}m^{-2}s^{-1}@E_0 = 7TeV)$	$index$	TS
J0534+2201	83.62+/- 0.01	22.01+/-0.01	0	2.22+/-0.03	(2.79+/-0.02)-(0.06+/0.01)×log(E/7TeV)	73022.4
J1826-1343	276.55+/-0.03	-13.73+/-0.04	0.18+/-0.04	1.32+/-0.27	2.57+/-0.08	463.619
J1839-0554	279.83 +/- 0.04	-5.92 +/- 0.04	0.23 +/-0.03	0.58 +/- 0.10	2.67 +/- 0.09	363.421
J1844-0330	281.01 +/- 0.02	-3.52+/-0.03	0.39+/-0.03	1.05+/-0.07	2.58+/-0.05	1171.76
J1850-0005	282.65+/-0.03	-0.08+/-0.04	0.43+/-0.03	0.68+/-0.06	2.43+/-0.06	760.683
J1908+0615	287.08 +/-0.02	6.27+/-0.03	0.37+/-0.02	0.78+/-0.06	2.37+/-0.04	1787.25
J1928+1746	292.15 +/- 0.04	17.78 +/- 0.03	0.16+/-0.03	0.12+/-0.02	2.23+/-0.12	210.842
J1955+2845	298.91+/- 0.12	28.75 +/- 0.08	0.54+/- 0.07	0.18 +/- 0.04	2.07 +/- 0.14	154.59
J2018+3645	304.61+/-0.03	36.75+/-0.02	0.26+/-0.02	0.44+/-0.04	1.97+/-0.05	2295.72
J2031+4135	307.86+/-0.02	41.59+/-0.03	0.27+/-0.02	0.45+/-0.04	2.30+/-0.05	1981.36
J2107+5157	316.83+/-0.06	51.95+/-0.05	0.14+/-0.04	0.03+/-0.02	1.51+/-0.41	77.7091
J2227+6101	336.78+/-0.05	61.03+/-0.02	0.24+/-0.02	0.35+/-0.03	2.28+/-0.07	631.904

Table 1: The parameters of the spectral and morphological model of the 12 UHE sources in the energy range of 2-2-TeV. Due to the use of a multi-source model to fit the data, the source closest in angular distance to the 12 UHE sources was selected as their corresponding object at lower energies. The parameter R40 represents the distance containing 40% of the signal radiation from the source, and the TS for each source is calculated based on the best-fit model after subtracting the contributions of other sources.

4.3 LHAASO J1908+0621

The TeV emissions from this region discovered by the Milagro collaboration named MGRO J1908+06 in a survey of the Galactic plane [9]. The source was subsequently detected with H.E.S.S. above 300 GeV [10] and with VERITAS [11]. The H.E.S.S. observations showed that MGRO J1908+06 (HESS J1908+063) is an extended source, and a fit of a two-dimensional Gaussian function to the excess map yielded an intrinsic size of the TeV source of sigma = 0.34 degree [10]. Although MGRO J1908+06 is very bright in gamma rays with a flux corresponding to 80% of the Crab Nebula flux at 20 TeV, no extended emission at other energies has so far been detected.

We conducted an analysis using data within a radius of 6 degrees centered on this source. The final analysis revealed the presence of 11 sources, as shown in Figure 3. The flux and spetrum index are abtained, and the gaussian template parameter of sigma is consistent with the extent measured by the HESS experiment. we found an extended source of approximately 1.0 degrees within a range of 0.5 degrees from LHAASO J1908+0621, and a larger extended radiation within a range of 1 degree. Since the contribution of diffuse gamma-ray background has not been considered in the analysis, further work is needed to analysis the association between the extended radiation and LHAASO J1908+0621. However, this provides a hint that if we want to further study the properties of LHAASO J1908+0621, it is necessary to consider the contribution of diffuse and even surrounding material distribution, as well as perform data analysis on a larger scale.

The results of the joint fitting of the WCDA and KM2A spectra are also obtained using a double power-law form. The results of the joint fitting indicate the presence of a slight break in the spectrum, which provides some constraints on determining the radiation mechanism of the source.

4.4 LHAASO J2032+4102

VHE emission from this region named TeV J2032+4130 regarded as unidentified(UNID) source was discovered serendipitously by the HEGRA imaging atmospheric Cherenkov telescope (IACT) system during observations made in the years 1999–2001. [12] It was the first TeV gamma-ray detection to have no obvious counterpart at any other wavelength and was also the first extended source to be discovered in the very high energy (VHE) range. in subsequent studies [13, 14], the

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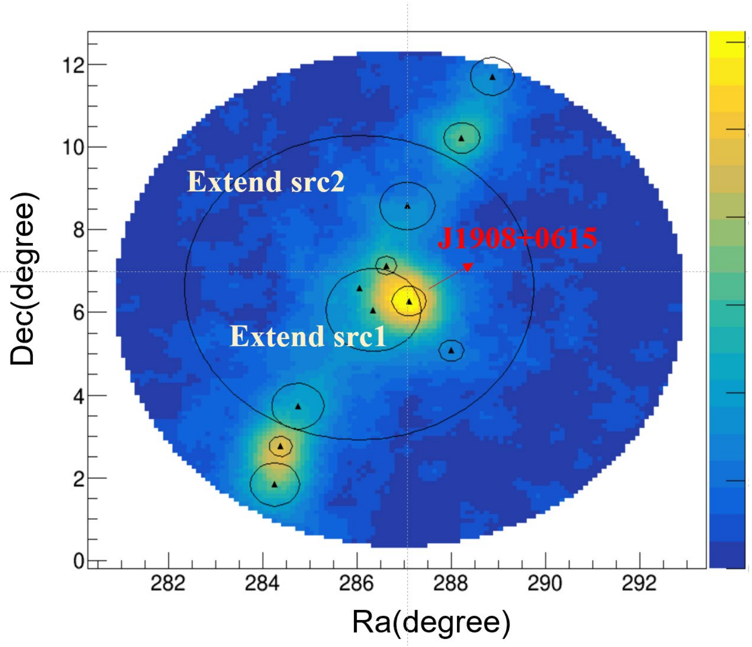

Figure 3: The sources near the J1908+0621 obtained from fitting

classification of the source was updated from UNID to the Pulsar Wind Nebula(PWN). The flux measured by HAWC [15] consistent with Milagro and ARGO[16] than the IACTs [12], indicates that possible additional emission components besides the PWN within the region.

By employing a Gaussian spatial template and a power-law spectral model, the radiation center and the Gaussian template parameter of sigma of LHAASO J2032+4102 is determined It exhibits slight extension, which is consistent with the measurement results of HAWC J2031+415 [17]. The flux at 7TeV measured which is consistent with 2HAWC J2031+415 [15] , and the spectrum index is consistent with veritas [18] . As shown in Figure 4, due to the small extent of the source, the positions measured by different experiments are consistent within one sigma of the Gaussian extension. This indicates that the measurements of the source's position by different experiments align within the expected range of its small extent. This consistency helps us accurately determine the location and morphology of the source and further investigate its physical properties and origin.

Additionally, we conducted a joint spectral fitting using a truncated power law function in form of $f(E) = \alpha \frac{E}{E0}^{-\beta} exp(\frac{E}{E_{cut}})$ ($\beta = 2.01 \pm 0.05, E_{cut} = 43.3 \pm 3TeV$) and obtained a spectral parameter with the $\chi^2/ndf = 4.4/7$.

5. Summary

In this study, we employed an advanced 3D likelihood method to analyze the data from WCDA and conducted observations of 12 high-energy regions within the Milky Way galaxy. We provided data on the energy spectra and morphologies of these sources in the 2-20TeV range. By combining high-energy data from KM2A, we obtained comprehensive spectral fitting results spanning the entire energy range. We anticipate that these results will contribute to further understanding the

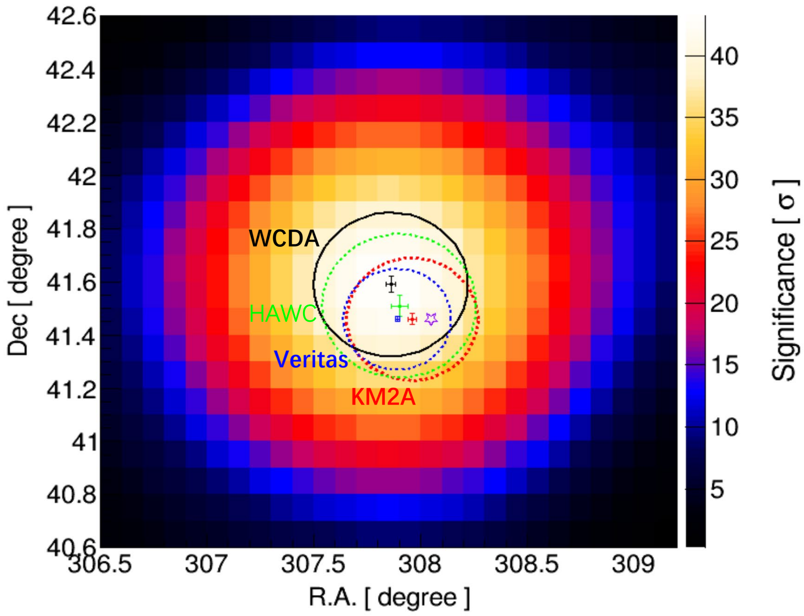

Figure 4: Position of TeV emission from TeV J2032+4130 measured by different experiment(VERITAS [11], HAWC[17], KM2A and WCDA). The solid dots of different colors represent the measured positions from different experiments, with the error bars representing one standard deviation (including statistical errors only). The radius of the circles of different colors are equal to one sigma of the Gaussian extension.

physical mechanisms of these gamma-ray sources and provide deeper insights into cosmic ray acceleration and high-energy astrophysical phenomena.

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