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Study on Gamma ray-binaries with the LHAASO data

Mariam Hasan,[a,b,c,*] **Shicong Hu,**[a,c] **Zhiguo Yao,**[a,c] **Zhang Bing**[a,c] **and The LHAASO collaboration**

[a] *State Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, 19B Yuquan Road, Shijingshan District, Beijing, China*

[b] *University of Chinese Academy of Sciencess, 100049 Beijing, China*

[c] *TIANFU Cosmic Ray Research Center, 1500 Kezhi Road, Tianfu District, Chengdu, Sichuan Province, China*

E-mail: mariamhasan@ihep.ac.cn

High-energy binary systems, especially those emitting TeV and ultra-high-energy gamma rays, provide critical insights into the extreme astrophysical processes involving compact objects and their companion stars. Observations from the Large High Altitude Air Shower Observatory (LHAASO), utilizing its WCDA and KM2A arrays, offer detailed analysis of key systems such as HESS J0632+057, PSR J2032+4127, LS 5039, LS I +61° 303 and GRS 1915+105. SS 433, however, has already been detected and published by LHAASO. These binaries, composed of compact objects like black holes or neutron stars, exhibit complex interactions that produce gamma-rays via jet emissions and accretion processes. Through spectral and spatial analysis, the study enhances our understanding of particle acceleration mechanisms, jet formation, and the broader implications of these systems in high-energy astrophysics. LHAASO's contributions significantly advance the understanding of astrophysical phenomena in extreme environments and support the testing of theoretical models in high-energy astrophysics.

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*Speaker

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1. Introduction

The study of high-energy binary systems, especially TeV binaries, is vital for understanding the dynamic processes in the universe. These systems typically involve a compact object, such as a black hole or neutron star, and a massive star. The Large High Altitude Air Shower Observatory (LHAASO) has provided crucial insights into such systems by detecting high-energy gamma rays, shedding light on the complex interactions between compact objects and their stellar companions.

This paper focuses on key binary sources observed by LHAASO, including well-known systems like GRS 1915+105 and recently detected systems like SS 433 w1 and LS I +61 303. These systems are particularly valuable due to their unique characteristics, offering a wide range of data for high-energy astrophysical research.

TeV gamma-ray emissions in these binaries are produced through interactions between the compact object's outflows and the surrounding stellar wind or interstellar medium. Analyzing the high-energy emissions and orbital characteristics of these systems provides insights into accretion disks, jet formation, and compact object interactions, making them essential for testing high-energy astrophysical theories.

2. The LHAASO Experiment and Data Analysis

The Large High Altitude Air Shower Observatory (LHAASO), located at 4,410 meters on Haizi Mountain in Daocheng, China, is a state-of-the-art facility designed to study cosmic rays and gamma rays across a vast energy range from sub-TeV to beyond 1 PeV. Fully operational since July 2021, LHAASO consists of three sub-arrays: the Km² Array (KM2A), the Water Cherenkov Detector Array (WCDA), and the Wide-Field Cherenkov Telescope Array (WFCTA) [1]. The WCDA, a 78,000 m² array of purified water, is focused on surveying very-high-energy gamma rays from sub-TeV to 20 TeV and is used to analyze diffuse Galactic plane emission [2] The KM2A, covering 1.3 km², features over 5,000 electromagnetic particle detectors and nearly 1,200 muon detectors, providing high detection efficiency and excellent angular and energy resolution. KM2A's performance, validated by Crab Nebula observations, achieves angular resolutions of less than 0.5° and energy resolutions under 25% for energies above 20 TeV, with remarkable hadron rejection capabilities [3].

All the binaries in the skymap of LHAASO was observed with LHAASO WCDA between March 2021 to July 2024 and with LHAASO KM2A between July 2021 to July 2024, accumulating a total livetime of 1137 days and 1064 days of data, respectively. We restricted the analysis to events with a zenith angle less than 50° to ensure high-quality reconstruction data. The sky map was constructed in the celestial coordinate system using right ascension (R.A.) and declination (Dec.) with a grid resolution of $0.1^\circ \times 0.1^\circ$ cells, where each cell contains the number of detected events based on their reconstructed arrival directions. To estimate the CR background in each cell, we applied the "direct integration method" [4] whereas, 3D likelihood fitting framework is developed to do the analysis.

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3. Unveiling Binaries: Insights from LHAASO

LHAASO's skymap includes six key binary systems shown in Table 1 with significances based on spatial analysis. Preliminary results for these sources including spectral analysis and spatial morphology are presented in the following section.

Table 1: Binary Sources in LHAASO Skymap.

TeVCat Name	Common Name	Distance (kpc)	Orbital Period	Significance (σ)
TeV J0632+058	HESS J0632+057	5.79	317.3 days	7[a]
TeV J2032+414	PSR J2032+4127	1.80	45-50 years	40[b]
TeV J1914+108	GRS 1915+105	9.40	33.5 days	14[a]
TeV J1826-148	LS 5039	2.50	3.9 days	6[a]
TeV J1910+050	SS 433 w1	4.5	13.1 days	9.8[a]
TeV J1913+049	SS 433 e1	5.5	13.1 days	8.3[a]
TeV J0240+612	LS I +61 303	2.0	26.496 days	9.2[b] | 6.2[c]

[a] Joint analysis using WCDA and KM2A data.
[b] Analysis using WCDA data only.
[c] Analysis using KM2A data only.

3.1 HESS J0632+057

HESS J0632+057 is a rare gamma-ray binary system located near the Monoceros supernova remnant at 1.5 kpc distance. It comprises a massive Be star (MWC 148) with effective temperature $T_{\text{eff}} \sim 30,000$ K, mass 13–16 $M_{\odot}$, and luminosity $L_{\text{bol}} \sim 10^4 L_{\odot}$, orbited by a compact object likely a neutron star or black hole [7]. The system exhibits strong orbital-phase-dependent variability in γ-ray and X-ray emissions, with periastron timing debated between phase 0.967 [5] (near emission plateau) and 0.663 [6] (near secondary peak).

For the joint analysis of HESS J0632+057, the targeted source was identified as point-like, located at R.A. = 98.305 ± 0.047°, Dec. = 5.841 ± 0.046° exhibits a spectral index of α = 2.874 ± 0.117. Additionally, a nearby bright source, modeled with a Gaussian morphology, was classified as an extended source at R.A. = 98.720 ± 0.088°, Dec. = 6.743 ± 0.087°, and an angular extension of 0.845 ± 0.094°. The full-time significance map and spectrum is shown in Figure 1 .

3.2 PSR J2032+4127

PSR J2032+4127 is a fascinating astronomical object that emits both gamma-rays and radio waves [8], Located in the Cygnus OB2 region. Recent observations have revealed its dynamic nature: it forms a binary system with the massive star MT91 213 (a B0Ve-type star weighing 15 solar masses) [9]. This pulsar holds particular interest due to its proximity to TeV J2032+4130, the first known very-high-energy (VHE; >100 GeV) gamma-ray source that initially lacked any clear identification. While current theories favor an association with a pulsar wind nebula from PSR J2032+4127 [10], the exact nature of TeV J2032+4130 remains uncertain, prompting further exploration of the relationship between these two sources.

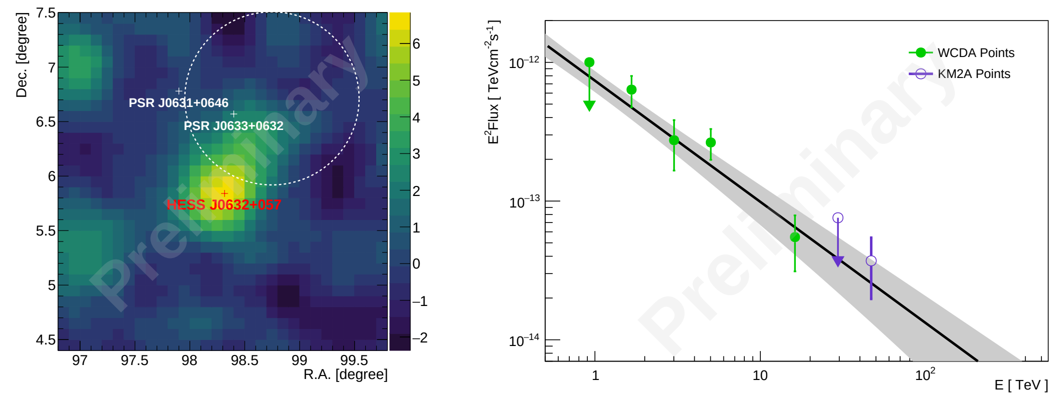

Figure 1: Significance maps is on left where LHAASO position is identified with red mark, and the VHE spectra of HESS J0632+057 is on right.

The WCDA analysis of PSR J2032+4127 reveals two extended gamma-ray sources, LHAASO J2031+4124 and LHAASO J2031+4147, modeled with Gaussian spatial extensions $0.223 \pm 0017°$ and $0.259 \pm 0.018°$, respectively and power-law spectra with spectral indices $\alpha = 2.362 \pm 0.018$ and $\alpha = 2.272 \pm 0.044$. These sources, detected with high significance 40σ, exhibit energy-dependent emission across multiple bins, suggesting non-thermal processes potentially associated with pulsar wind nebulae or other high-energy phenomena in the region. The full-time significance map and spectrum is shown in Figure 2. As this is a preliminary result based on WCDA data, the joint analysis is still in progress and will be updated in this proceeding soon.

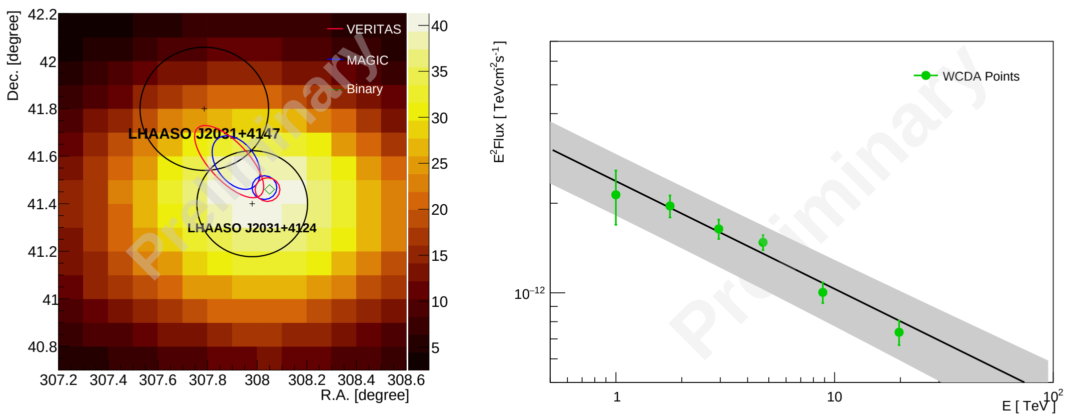

Figure 2: Significance maps is on left where LHAASO WCDA position is identified with black mark, and the VHE spectra of PSR J2032+4127 is on right with best fit result.

3.3 GRS 1915+105

GRS 1915+105, the archetypal Galactic microquasar, was discovered in 1992 as a variable X-ray source exhibiting relativistic jets with apparent superluminal motion ($v \sim 0.8c$ [11]. Multiwavelength monitoring over three decades revealed quasi-periodic oscillations, anti-correlated

X-ray/radio flaring, and a significant 2018 X-ray flux decline, interpreted as either obscuration or a state transition, making GRS 1915+105 a unique laboratory for studying accretion–jet coupling in extreme environments.

In this proceeding, we present a joint analysis of GRS 1915+105 using both WCDA and KM2A data from LHAASO. This approach provides a broader energy coverage compared to the analysis reported in the microquasar paper [19], which focused exclusively on the high-energy KM2A data. The source morphology is well described by a Gaussian model, yielding an extension of $0.332 \pm 0.038°$, with the centroid located at R.A. = $288.673 \pm 0.042°$ and Dec. = $10.898 \pm 0.052°$. Spectrally, the emission follows a log-parabola distribution characterized by a photon index of $\alpha = 2.428 \pm 0.073$, with a pivot energy at 10 TeV. As shown in Figure 3, the source lies in close proximity to PSR J1914+1054g and the supernova remnant SNR G045.7−0.4.

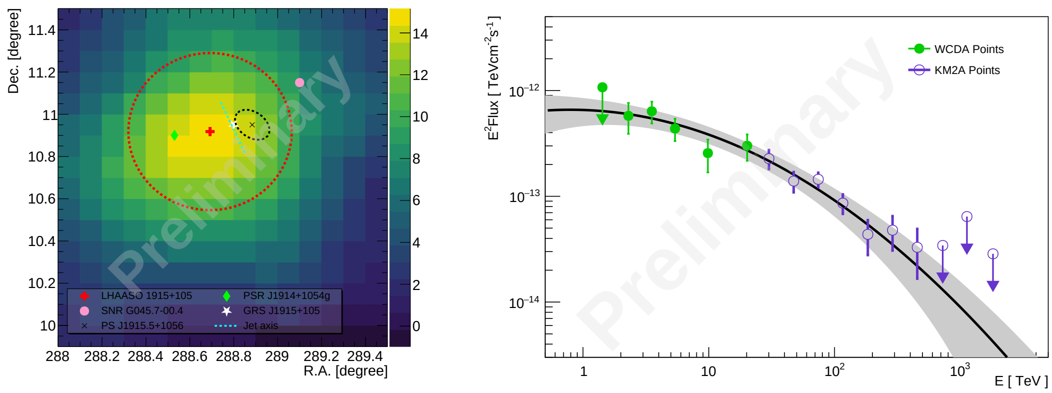

Figure 3: Significance map by LHAASO for full time period (left) and the VHE spectra of GRS 1915+105 observed by LHAASO over the entire time period is on right with best fit result.

3.4 LS 5039

LS 5039 is a high-mass binary system comprising a compact object in orbit around an O6.5V-type star. The companion star has an estimated mass of 23 $M_\odot$ and a radius of 9.3 $R_\odot$, while the compact object, with a mass near 3.7 $M_\odot$ [17], remains unidentified likely a neutron star or black hole. The system exhibits persistent radio outflows extending up to 2000 AU, suggesting a microquasar nature [18].

Using a joint analysis of WCDA and KM2A data, the best-fit position of the TeV source is modeled as a point source located at R.A. = $276.633° \pm 0.038°$ and Dec. = $-14.439° \pm 0.059°$, which differs from the binary by approximately 0.3°. The spectral energy distribution (SED) is modeled as a power law with $\alpha = 3.199 \pm 0.103$. In Figure 4, the sky map in the left panel shows the clear detection of the source, and the energy spectrum in the right panel presents the flux values from both WCDA and KM2A data points, with a power-law fit applied. These results provide a detailed characterization of the high-energy emission from LS 5039, enhancing our understanding of its particle acceleration mechanisms. In parallel, another LHAASO collaborator is also analyzing this binary using WCDA and KM2A data separately.

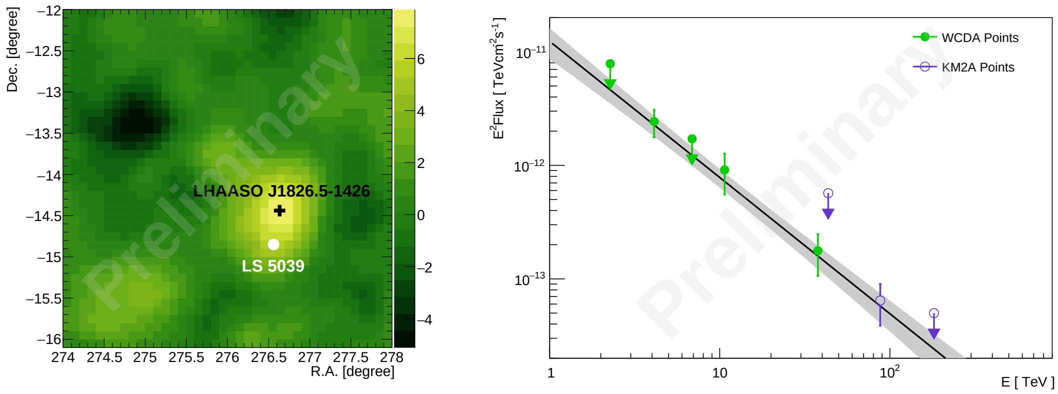

Figure 4: Significance map and SED of LHAASO identified position of LS 5039 for full time period

3.5 SS 433

SS 433, identified as the first microquasar in 1977 [12], is a high-mass X-ray binary containing an unidentified compact object accreting material from a massive companion star. Its relativistic jets produce distinct eastern and western lobes within the surrounding W50 radio nebula [13]. The detection of multi-TeV gamma-ray emission from these lobes by HAWC in 2018 motivated further observations by Fermi-LAT, NuSTAR, and H.E.S.S., which primarily focused on the eastern lobe due to observational challenges with the western lobe [14]. The western lobe's analysis is complicated by contamination from diffuse Galactic emission and its proximity to the bright gamma-ray source MGRO J1908+06.

A comprehensive joint analysis of SS 433 has been completed and submitted for publication [19]. The results include high-resolution significance and spectral maps, offering insights into the high-energy emission and particle acceleration mechanisms associated with the system.

3.6 LS I +61° 303

LS I +61° 303 is the third system classified as a gamma-ray binary observed in very high energy (VHE) gamma rays, following PSR B1259–63 and LS 5039. Since its initial detection as an unidentified Galactic MeV gamma-ray source by the Cos-B satellite in 1977, LS I +61° 303 has been extensively studied across the electromagnetic spectrum from radio to gamma rays [15]. The system comprises a massive B0 Ve star and a compact object with uncertain nature; it may be a pulsar orbiting the Be star within a circumstellar disc or an accreting black hole. Recent detection of a 269.196 ms periodic signal by the FAST radio telescope in January 2021 supports the pulsar hypothesis [16].

The TeV gamma-ray emission from LS I +61° 303 was independently studied using WCDA and KM2A data. Figure 5 presents the significance maps around LS I +61° 303 at two different energies. The best-fit positions, derived using a 2D Gaussian model, are R.A. = $40.10° \pm 0.07°$, Dec. = $61.33° \pm 0.04°$ for WCDA, and R.A. = $40.18° \pm 0.10°$, Dec. = $61.16° \pm 0.05°$ for KM2A. No significant spatial extension was observed, with 95% confidence level upper limits of 0.22° (WCDA) and 0.25° (KM2A) on the source size. The gamma-ray energy spectrum follows a power-law model,

$dN/dE = N_0(E/10\,\text{TeV})^{-\Gamma}$, where $N_0 = (2.18{\pm}0.20){\times}10^{-15}\,\text{TeV}^{-1}\,\text{s}^{-1}\,\text{cm}^{-2}$ and $\Gamma = 3.00{\pm}0.05$. The integral flux above 1 TeV corresponds to approximately 3.8% of the Crab Nebula flux. These results are broadly consistent with previous observations by MAGIC and VERITAS.

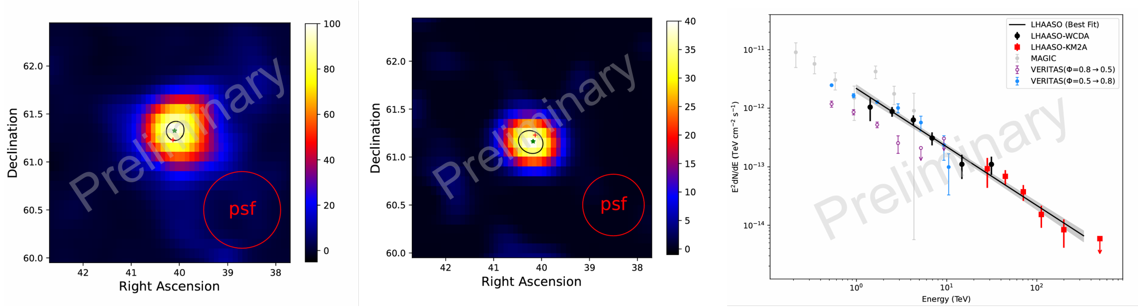

Figure 5: Significance maps of LS I +61° 303 obtained with WCDA (left, 1.5–30.5 TeV) and KM2A (middle, >25 TeV). Right: SED measured by LHAASO.

4. Conclusion

The observations of high-energy binary systems by LHAASO have provided groundbreaking insights into the astrophysical processes that govern some of the universe's most extreme environments. By investigating systems such as GRS 1915+105, SS 433, LS 5039, and LS I +61° 303, this research has deepened our understanding of the complex mechanisms behind TeV and ultra-high-energy gamma-ray emissions. These systems, involving interactions between compact objects and massive companion stars, reveal critical phenomena such as particle acceleration, jet formation, and accretion processes. The high-resolution spectral and spatial data collected by LHAASO not only enhance our understanding of these dynamic systems but also offer crucial validation for theoretical models of high-energy astrophysics. With its exceptional sensitivity and comprehensive observational range, LHAASO is positioned at the forefront of high-energy cosmic research, and its continued observations will play an essential role in advancing our knowledge of the most energetic processes in the universe.

All the results presented in this proceeding paper are preliminary and subject to further refinement and improvement.

5. Acknowledgment

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