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Possible VHE gamma emission from PWN tail of PSR J1740+1000

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R.F.Xu,[a,b,*] **K.Wang**[c,d] **and LHAASO Collaboration**

[a] *Institute of High Energy Physics, Chinese Academy of Sciences, 100049 Beijing, China*
[b] *University of Chinese Academy of Sciences, 100049 Beijing, China*
[c] *School of Astronomy and Space Science, Nanjing University, Nanjing 210023, Jiangsu, People's Republic of China*
[d] *Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210023, People's Republic of China*

E-mail: xurenfeng@ihep.ac.cn

In this report, we present an analysis of a gamma source with very high energy (VHE) in close proximity to the PSR J1740+1000. Our observations, carried out using the LHAASO-KM2A instrument, yielded a remarkably high significance level exceeding 12σ (5.4σ) above 25 TeV (100 TeV). The precise fitting position was determined as RA = $265.01 \pm 0.03°$, Dec = $9.79 \pm 0.04°$, exhibiting an offset of approximately 0.22° from the pulsar's location and aligning almost perfectly with the trace of its proper motion.In power-law shape,α and N_0 are 3.15 ± 0.17 and $0.37 \pm 0.04 \times 10^{-16}\mathrm{TeV}^{-1}, \mathrm{cm}^{-2}, \mathrm{s}^{-1}$ at $50\,TeV$,respectively.

The pulsar most associated with our observations is PSR J1740+1000, which is a middle-aged pulsar exhibiting a prominent X-ray tail. This pulsar is located at the high galactic latitude and it is considered a important potential pulsar halo candidate by the HAWC Collaboration. Nevertheless, our analysis did not reveal any significant extension. Considering the positional coincidence, we favor the hypothesis that the origin of the gamma emission lies within the pulsar wind nebula (PWN) tail. However, it is crucial to note that alternative explanations, such as a distant off-beam pulsar, contributing to the halo, cannot be conclusively ruled out totally.

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1. INTRODUCTION

Pulsars, known for their immense power, generate energetic nebulae that interact with the surrounding medium and decelerate at the termination shock. This interaction leads to the acceleration of particle pairs to exceptionally high energies, forming an extended structure known as a pulsar wind nebula (PWN). PWNe have been extensively observed across various wavelengths, ranging from radio to gamma rays, and constitute a significant fraction of TeV sources.

Due to the natal kick velocity imparted during the supernova explosion, most pulsars eventually move beyond the confines of their parent supernova remnants (SNRs) during the Sedov-Taylor phase of remnant expansion, engaging with the interstellar material. Certain pulsars travel supersonically through the interstellar medium (ISM), resulting in a distorted PWN adopting a droplet-shaped morphology with an extended tail emanating from the bow shock. Further insights on the bow shock phenomenon can be found in comprehensive reviews such as [1]. Notably, X-ray observations have revealed the presence of bow shock PWNe in middle-aged pulsars, commonly referred to as the "Guitar nebula" and the "Lighthouse nebula" [2, 3]. However, to date, no confirmed gamma-ray emissions originating from these tails have been detected.

The limited field of view and focus on synchrotron processes in a localized region restrict the extent of information garnered from X-ray observations. Consequently, our understanding of electron transport and evolution across a broader volume remains limited. In contrast, several pulsars, such as Geminga [4], have exhibited extended gamma-ray emission in the form of TeV Halos. However, the mechanisms governing electron escape from Bow Shock PWNe and subsequent diffusion leading to the formation of the Halo remain unclear. The scarcity of Pulsar Halo samples hampers our ability to unravel these intricate mechanisms. Moreover, the precise definition of a Pulsar Halo lacks clarity. Adhering to the depiction in [5], many middle-aged pulsars should exhibit Halo-like structures, but this assumption necessitates confirmation through observations from highly sensitive observatory such as LHAASO.

In this study, we focus our analysis on the pulsar PSR J1740+1000, an object of particular interest. With an estimated age of approximately 114 kyr, PSR J1740+1000 was discovered in a survey conducted by the Arecibo observatory in 2000. Situated at a Galactic latitude that is significantly above the Galactic plane, it might be born from a halo-star progenitor[6]. This pulsar exhibits intriguing characteristics that warrant closer examination. Notably, it possesses a large spin-down luminosity of approximately $2.3 \times 10^{35}\ erg\ s^{-1}$ and is located at a relatively close distance of about 1.2 pc. X-ray observations of PSR J1740+1000 reveal an extended and elongated tail spanning approximately $5.5'$, suggesting a possible alignment towards the galactic plane [7]. However, the search for gamma-ray emissions from the tail by the VERITAS Collaboration yielded inconclusive results, providing only an upper limit of 10^{-13} cm^{-2} s^{-1} within the 1 – 10 TeV energy range [14]. Additionally, the HAWC Collaboration reported the presence of a faint gamma-ray source with an offset of 0.13°[13]. In light of these findings, our analysis will leverage the high-energy data acquired by LHAASO to further investigate the possible radiation origins associated with PSR J1740+1000.

2. The LHAASO Experiment

The Large High Altitude Air Shower Observatory (LHAASO) was a new generation cosmic hybrid detector array located at Mt. Haizi ($4410 m a.s.l., 29°21'27.56''N, 100°08'19.66''E$) in Daocheng, Sichuan province, P.R. China. It was designed with unprecedented sensitivity from GeV to EeV and had open a the era of UHE gamma-ray astronomy. Thus far,its two sub-arrays(KM2A,WCDA) work with high performance for more than 1 year, the specific stats refer to [8][9].

LHAASO-KM2A and LHAASO-WCDA were 1.3 km^2 array and water Cherenkov detector array,respectively. The utilization of muon detectors (MDs) enables LHAASO-KM2A to effectively discriminate against the majority of cosmic ray (CR) events, resulting in a remarkable survival rate of only 0.0001% for CR shower events above ~150 TeV. Capitalizing on its substantial effective area and high rejection capabilities, KM2A establishes itself as the most sensitive observatory for gamma rays above 100 TeV over an extended duration.

3. Data analysis method and result

Here a live time about 900 days contain 1/2,3/4 and full array data of LHAASO-KM2A are chooses, date span from December 27,2019, to September 30, 2022. We performer reconstruct of direction and energy, classified the events to photons or Cosmic particles according to the muons. CR background is estimate by the 10h direct integration method[10]. Than we unitize the 3D likelihood fit method to fit the morphology combine the spectrum. The significance of the source with different templates after convolution with point spread function(PSF) is given by $TS = 2ln(\mathcal{L}_{s+bkg} - \mathcal{L}_{bkg})$, $\mathcal{L}_{s+bkg}$,$\mathcal{L}_{bkg}$ are maximum likelihood value of source model hypothesis and without source. Precise spectrum energy distribution(SED) is estimated by forward-folding method[8].

For our analysis, we had selected a region of interest (ROI) measuring $8.4 \times 8.0°$ centered on PSR J1740+1000. The celestial map was partitioned into grid cells of size $0.1 \times 0.1°$, and the energy range was logarithmically divided into bins with a width of 0.2 per bin. At the high latitude of approximately 20° under investigation, we deem the impact of diffusion gamma rays to be negligible. Within this context, our analysis has found a significant gamma source in close proximity to PSR J1740+1000, designated as LHAASO J1740+0948. This gamma source exhibits an extension to energies surpassing 100 TeV, yielding a significance of 5.4σ (Total 12σ significance). Remarkably, LHAASO J1740+0948 is found in close proximity to the extrapolated path of the PWN tail, as visually depicted by the purple striped line in Figure1. However, a considerable angular offset of approximately 0.22° exists between the position of the pulsar and that of LHAASO J1740+0948. Moreover, the observed profile displays pronounced deviations from the pulsar's emission profile, reaching a statistical significance exceeding 3σ. Notably, such a significant angular offset is unexpected at these high energies, as the high-energy electrons emanating from the PWN rapidly cool down.

We conducted a series of tests utilizing different templates,however,none exhibited a significant improvement compared to the Point template. This implies that there is no compelling evidence for any particular morphological structure or extension. Applying the same methodology as described

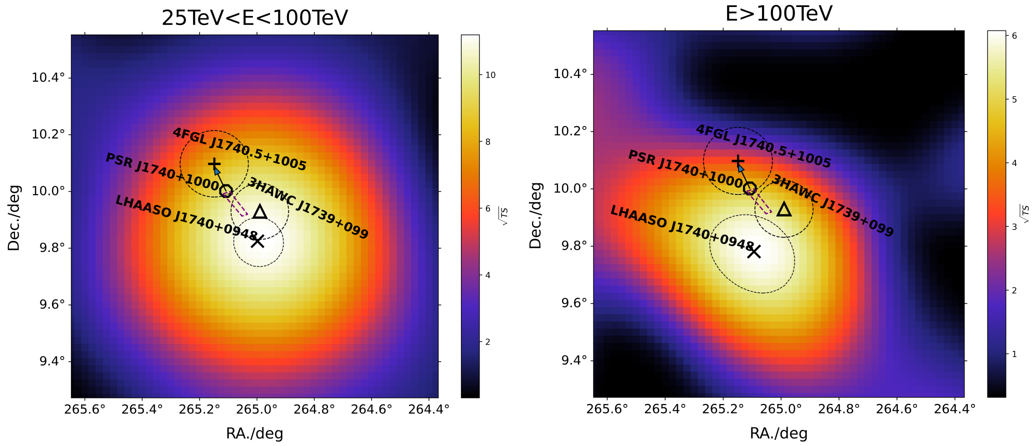

Figure 1: The figure presents a significance map centered around LHAASO J1740+0948, focusing on the energy range of 25 TeV to 100 TeV (and extending beyond 100 TeV on the right side). The best-fit position of the source is indicated by a black cross symbol, while the position provided by the 3HAWC catalog is represented by a triangle symbol. The circle denotes the position of PSR J1740+1000, and the plus symbol represents the position of the corresponding Fermi-LAT source. Each dashed line circle corresponds to the 95%error bound of the respective sources(dash line circle the LHAASO J1740+0948 represents the 3σ range). Notably, the X-ray observations reveal a distinctive tail extending approximately $5.5'$ from the pulsar, as depicted by the striped shape. Additionally, an arrow pointing towards the front of the pulsar indicates its direction of proper motion.

in [11] to establish a 95% confidence level upper limit, we obtained a small value of 0.14°. Henceforth, we will treat the source as a point source based on these results.

Figure 2 shows the fitted spectrum using both Power-law and logparabola models. Power-law fit give a flux of $0.37 \pm 0.04 \times 10^{-16}\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at 50TeV. The logparabola fit yields a higher significance, with $\Delta\mathrm{TS} \approx 16$. The peak of the spectrum is observed at approximately 30 TeV, as indicated by the fitted parameters in the upper right corner of the figure. The observed data suggests that the cutoff energy appears to be in the vicinity of several tens of TeV, indicating that it does not extend to the PeV (Petaelectronvolt) regime.

4. DISCUSSIONS

4.1 Multiwavelength Observations

The most nearby TeV source is the 3HWC J1739+099 from 3HAWC catalog[13], this source exhibits a relatively low significance level and is located 0.13° away from PSR J1740+1000. The catalog describes its spectrum as being fitted with a single power-law model, with a flux of $(3.3 \pm 0.8)\times 10^{15}$, $\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 7 TeV and a spectral index of -1.98. It's Spectrum is align well with the LHAASO J1740+0948 at dozens TeV with a small angular separation of approximately 0.13°.This suggests the possibility that we have detected the same source as the HAWC Collaboration. For searching the high energy photons emission from the PWN tail, VERITAS also pointing to the Pulsar with accumulating a total exposure time of 12.8 hr,unfortunately,no significance emission from the X-ray tail or even longer contribution is found[14]. As a result, them report the 95% C.L. upper limit

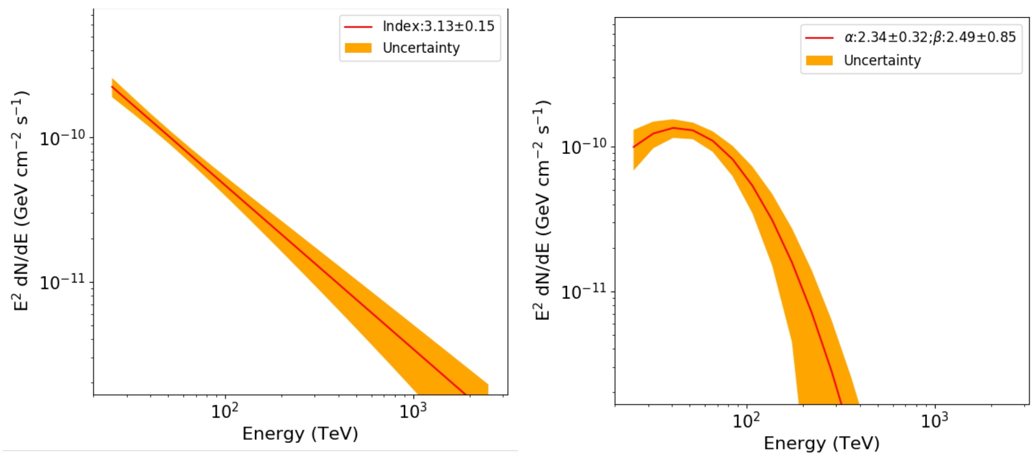

Figure 2: Left panel show the fitting result with Power-law, while right is fitted with logparabola shape

and estimate the potential gamma flux which hint only a few-fold improvement in sensitivity would be advantageous. In fact the PSR J1740+1000 was identified as a gamma Pulsar, it was observed in GeV regime named 4FGL 1740.5+1005[15], this source was located ahead of the Pulsar,more far away from where we observed. X-ray observations of the PWN reveal a tail morphology spanning 5.5′ to 7.0′ in the 0.3 − 10 keV energy range, with a flux $F_X = (1.93 \pm 0.06) \times 10^{-13}$ erg cm^{-2} s^{-1}. Unfortunately, due to the significant offset between the Pulsar and the LHAASO J1740+0948, our fitted position lies outside the region covered by X-ray observations.

As mentioned in the previous section, a significant angular offset raises questions regarding whether the gamma source may be powered by another pulsar or an active celestial object. Consequently, we aim to assess the possibility of association between the pulsar and 1LHAASO 1740+0948u, following the methodology presented in [12]. By counting the number of pulsars within a $20 \times 5°$ rectangular region center on1LHAASO 1740+0948u, as obtained from the ATNF[1], we can evaluate the probability of chance coincidence within the offset circle. Given the sparsity of sources at high galactic latitudes, the chance coincidence probability is estimated to be lower than 0.22%, providing strong evidence at a significance level exceeding 3σ for the association between1LHAASO 1740+0948u and the pulsar. Subsequent discussions and analyses will be based on this assumption. [1]

4.2 Pulsar Halo or PWN tail?

Differing from the Geminga region, the high galactic latitude in our observed region implies a lower influence from other materials and sources. The density of $n_{\rm H}$ in the vicinity is estimated to be around 1 per cm^3, rendering the consideration of a hadronic origin unnecessary. In the Pulsar Halo scenario, With such a high spin down luminosity(2.3×10^{35} erg s^{-1}) and interacting with ISM currently lead to a extension TeV Halo. A very similar pulsar is the J0622+3749 which had observed 0.4° Halo by LHAASO recently [16]Given the proximity of PSR J1740+1000, it is expected that its Halo extension would be comparable or even larger. However, the analysis results demonstrate minimal differences between the 2D Gaussian, Diffusion, and Point templates. The upper limit

[1]https://www.atnf.csiro.au/research/pulsar/psrcat/

extension being only 0.14°, this would imply a diffusion coefficient more than ten times smaller. Additionally, the significant offset between the pulsar and LHAASO J1740+0948 does not favor the Pulsar Halo scenario. Simulations of the morphology conducted by [17] indicate a maximum offset of approximately $\Theta = 3^\circ(E/1,\mathrm{TeV})^{-0.77}(v_{\mathrm{prop}}/400,\mathrm{km},\mathrm{s}^{-1})(d/2,\mathrm{kpc})^{-1}$ when assuming a fixed magnetic field of $3,\mu G$. To account for this offset, the proper motion velocity of the pulsar would need to exceed several thousand km/s, significantly surpassing the upper limit velocity of 60 mas/yr (280 km/s) [18]. Collectively, these pieces of evidence fail to support the assumption that 1LHAASO 1740+0948u is the TeV Halo associated with PSR J1740+1000.

Only considering the bright X-ray tail part is insufficient to explain the observed gamma flux. In fact, due to the slower cooling process of Inverse Compton compared to synchrotron radiation, the gamma-ray tail should extend further. The VERITAS Collaboration has suggested that a longer tail containing more electrons contribution, it leads a large flux than observed. Thus, the PWN tail alone is capable of generating the observed gamma luminosity. Additionally, we have constructed a narrow ellipse to simulate the shape of the tail. The fitting results indicate that the significance of the template is slightly lower than that of the point source model. In other words, we cannot currently differentiate between the tail shape and the point source. However, we cannot dismiss the possibility that the emission originates from the PWN tail. Interestingly, in the context of the PWN tail scenario, the position and offset can be consistently explained. The fitted position represents the weighted center of the tail, making the observed offset reasonable.

5. Conclusions

We conducted an analysis using approximately 900 days of KM2A data in the region of PSR J1740+1000, which led to the discovery of a significant gamma source, 1LHAASO 1740+0948u, identified as the 3HWC J1739+099 in the third HAWC Catalog. Our fitting results indicate that it is a point source located at RA = 265.01 ± 0.03° and Dec = 9.79 ± 0.04°, with a significance of 12σ above 25 TeV. The spectral index of the source, modeled as a power-law, is determined to be 3.15 ± 0.17, with a flux of $0.37 \pm 0.04 \times 10^{-16}\mathrm{TeV}^{-1},\mathrm{cm}^{-2},\mathrm{s}^{-1}$ at 50 TeV. The upper limit of the source extension is estimated to be approximately 0.14°. Notably, the position of the source exhibits a significant deviation from the expected location of the pulsar, these evidences suggesting that it is unlikely to be a TeV Halo associated with PSR J1740+1000. Instead, it is plausible that the emission originates from the pulsar wind nebula (PWN) tail. However, the lack of X-ray observations hinders our ability to exclude other potential scenarios.

LHAASO, boasting a wide coverage and an exceptional duty cycle nearing 100%, plays a pivotal role in our research. Its unparalleled capacity to detect a vast number of events offers immense potential for a comprehensive analysis. With the accumulation of more data over an extended period, we can delve deeper into the intricate details of morphology, energy-dependent offsets, and precisely pinpoint the source's location at high energies. Furthermore, by incorporating multiwavelength data, we anticipate uncovering invaluable insights and unraveling the enigmatic nature of this phenomenon.

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References

[1] Bykov A M, Amato E, Petrov A E, et al. Space Science Reviews, 2017, 207: 235-290.doi:10.1007/s11214-017-0371-7

[2] Romani R W, Cordes J M, Yadigaroglu I A. The Astrophysical Journal, 1997, 484(2): L137. doi:10.1086/310796

[3] Pavan L, Bozzo E, Pühlhofer G, et al.Astronomy Astrophysics, 2011, 533: A74. doi:10.1051/0004-6361/201117379

[4] Abeysekara A U, Albert A, Alfaro R, et al. Science, 2017, 358(6365): 911-914. doi:10.1126/science.aan4880

[5] Giacinti G, Mitchell A M W, López-Coto R, et al. Astronomy and Astrophysics, 2020, 636. doi:10.1051/0004-6361/201936505

[6] McLaughlin, M. A., Arzoumanian, Z., Cordes, J. M., et al. 2002, Astrophys. J., 564, 333. doi:10.1086/324151

[7] Kargaltsev, O., Misanovic, Z., Pavlov, G. G., et al. 2008, Astrophys. J., 684, 542. doi:10.1086/589145

[8] Aharonian, F., An, Q., Axikegu, et al. 2021, Chinese Physics C, 45, 025002. doi:10.1088/1674-1137/abd01b

[9] Aharonian, F., An, Q., Axikegu, et al. 2021, Chinese Physics C, 45, 085002. doi:10.1088/1674-1137/ac041b

[10] Fleysher, R., Fleysher, L., Nemethy, P., et al. 2004, Astrophys. J., 603, 355. doi:10.1086/381384

[11] Cao, Z., Aharonian, F., An, Q., et al. 2023, arXiv:2305.17030. doi:10.48550/arXiv.2305.17030

[12] Mattox, J. R., Schachter, J., Molnar, L., et al. 1997, Astrophys. J., 481, 95. doi:10.1086/304039

[13] Albert, A., Alfaro, R., Alvarez, C.,et al. 2020, Astrophys. J., 905, 76. doi:10.3847/1538-4357/abc2d8

[14] Benbow, W., Brill, A., Buckley, J. H., et al. 2021, Astrophys. J., 916, 117. doi:10.3847/1538-4357/ac05b9

[15] Abdollahi, S., Acero, F., Ackermann, M., et al. 2020, , 247, 33. doi:10.3847/1538-4365/ab6bcb

[16] Aharonian F, An Q, Bai L X, et al. Physical Review Letters, 2021, 126(24): 241103. doi:10.1103/PhysRevLett.126.241103

[17] Zhang, Y., Liu, R.-Y., Chen, S. Z., et al. 2021, Astrophys. J., 922, 130. doi:10.3847/1538-4357/ac235e

[18] Halpern J P, Bogdanov S, Gotthelf E V. The Astrophysical Journal, 2013, 778(2): 120. doi:10.1088/0004-637X/778/2/120