Multi-wavelength Analysis of Unassociated LHAASO TeV Sources using HAWC Observatory

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Ultra-high-energy gamma-ray sources can be potentially classified as Galactic PeVatrons, that accelerate cosmic-rays up to PeV energies. These accelerated cosmic rays can interact via hadronic processes with a nearby ambient molecular cloud, resulting in the production of gamma rays and neutrinos. The Large High Altitude Air Shower Observatory (LHAASO) collaboration published a catalog of sources in which they categorized 14 sources as "unassociated/associated only with a GeV counterpart". These sources are not extensively observed at other wavelengths, and some are opaque indicating a potential obscuration by a molecular gas cloud. The High Altitude Water Cherenkov (HAWC) observatory surveys the very-high-energy sky in the energy range from 300 GeV to greater than 100 TeV. Its wide field of view makes it particularly suitable for studying large, extended regions of emission that often contain multiple point and diffuse sources of gamma rays. We present a preliminary analysis of 1LHAASO J2027+3657 using 2860 days of HAWC data, 16 years of Fermi-LAT data and archival Chandra data comprising of ~ 45 ks ACIS-I observation. We show that this analysis could advance our understanding of such obscured sources and provide a direct probe of cosmic-ray acceleration in the galaxy.

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1. Introduction

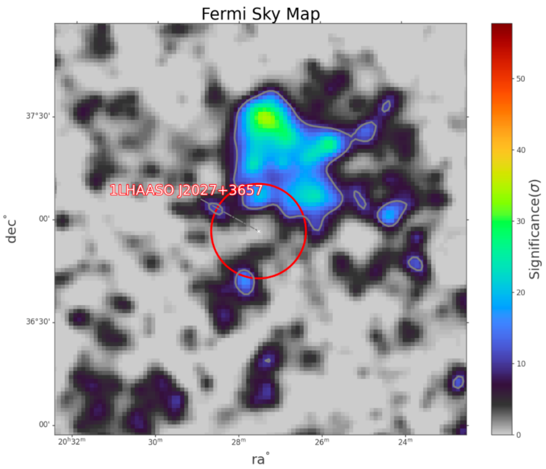
The study of the ultra-high-energy(UHE; > 10^{14} eV) gamma-ray sky began with the detection of emission from the Crab Nebula above 100 TeV by the Tibet-ASγ experiment [1]. In 2020, the High-Altitude Water Cherenkov Observatory (HAWC) published its first UHE gamma-ray catalog, identifying three additional sources exceeding 100 TeV [2]. These discoveries marked the beginning of the systematic exploration of sources in the UHE gamma-ray regime. A major leap came with the Large High Altitude Air Shower Observatory (LHAASO), which reported 12 UHE sources in its first catalog[3]. In 2023, LHAASO expanded its gamma-ray source catalog by adding new sources totaling up to 90, including 43 sources with gamma-rays above 100 TeV above 5σ threshold[4]. Out of these 90 sources, 15 were detected with either a GeV counterpart in Fermi-LAT or has no other associations in other wavelengths. Even with these advancements of ground-based observatories extended into the UHE domain, the nature of the objects producing the gamma-ray emission within these sources such as supernova remnants (SNRs), pulsars and their wind nebulae (PWNe), pulsar halos, or star-forming regions(SFRs), remains elusive. To deepen our understanding on the physical nature and origin of these extreme accelerators, multi-wavelength follow-up studies at lower energies and other wavelengths are crucial. Imaging atmospheric Cherenkov telescopes (IACTs) such as VERITAS, H.E.S.S., and MAGIC play a vital role in this effort. With their superior angular resolution ($\leq 0.1^\circ$), IACTs can provide detailed morphological and spectral information, offering a complementary view that helps clarify the identity and emission mechanisms of UHE gamma-ray sources

In this work, we present the preliminary analysis of one of the 15 unassociated LHAASO sources, 1LHAASO J2027+3657 hereafter referred to as J2027, using data from HAWC, Fermi-LAT, and Chandra X-ray observations. J2027 is located near the bipolar star-forming region Sharpless 2-106 (S106). In addition, we examine the distribution of molecular clouds in the vicinity of J2027 using ^{12}CO DAME Survey[5] and investigate the possibility of a hadronic interaction between the star-forming region and the surrounding molecular clouds.

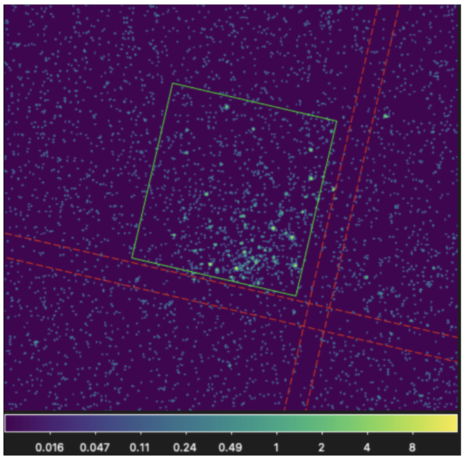
2. Data Analysis

In this work, we use data from HAWC, Fermi-LAT and Chandra X-ray observatories to model the multi-wavelength scenario for 1LHASO J2027+3657. For HAWC, we analyze the region around J2027, using 2860 days of data, with the 3ML framework [6]. The Fermi-LAT analysis uses data collected between 4 August 2008 and 20 July 2024 with energies from 200 MeV up to 1 TeV. Data reduction, event selection, and time filtering, were performed with `fermitools` v2.2.0 and `fermipy` v1.1.6 [7]. We also revisit a single archival Chandra observation at S106 - a $\sim$ 45 ks ACIS-I observation(Observation ID 1893)- to investigate possible connections between the X-ray emission and the gamma-ray emission observed by *Fermi*-LAT and HAWC. This observation was previously analyzed in [8], where X-ray emission from point sources, including the central object IRS 4, within S106 was reported.

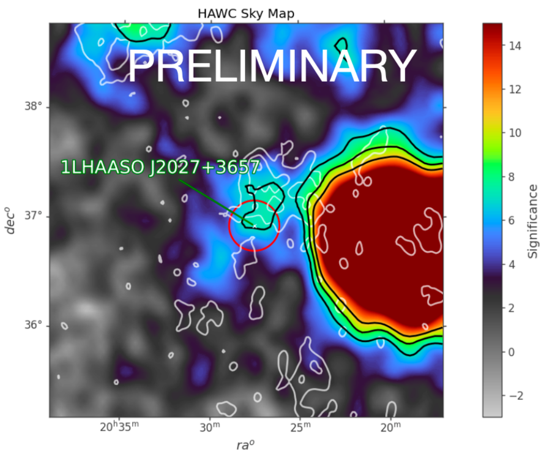
The HAWC analysis is done using the reconstructed data above 1 TeV with energies estimated with the neural network energy estimator [9]. A systematic source search pipeline is employed, incorporating Hermes templates [10] to model the diffuse background emission (DBE), which



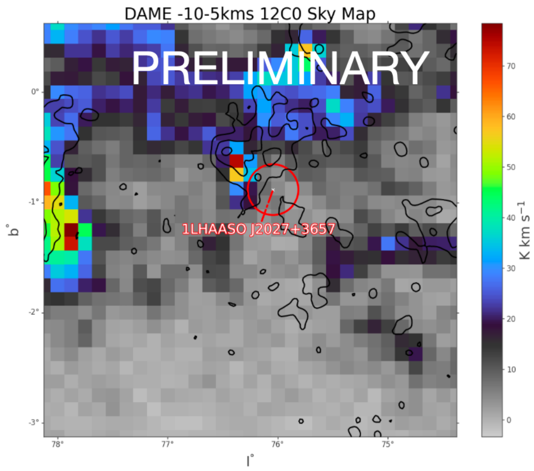
(a) *Fermi*-LAT (1 GeV - 1 TeV) significance map of the region. The red circle shows the extent of 1LHAASO J2027+3657.



(b) The Chandra ACIS-I image of S106, with the source region ($\approx 2' \times 2'$) highlighted in green. The red dashed regions in the image are the borders of the ACIS chips.



(c) HAWC pre-trial significance map made by assuming a point-source hypothesis and power-law spectrum with an index of -2.7 from 1 TeV < E_{rec} < 316 TeV. The black contours show the $5, 7, 9\,\sigma$ significance of the HAWC map and the white contours are from the *Fermi*-LAT extended source.



(d) ^{12}CO distribution in the region surrounding J2027. The black contours are the contours from the *Fermi*-LAT extended source.

Figure 1

accounts for both Galactic diffuse emission (GDE) and unresolved sources [11]. For the *Fermi*-LAT analysis, the region of interest (ROI) is defined as a circular area with a 20° radius centered at the location of J2027 (R.A., Dec) = (306°.88, 36°.95). The Fermi-LAT instrument response function version P8R3-SOURCE-V3 is used in the analysis, with maximum value of the zenith angle of observation is 90° and (`gll_iem_v07.fits`) diffuse emission template is used to model the diffuse background model.

The analysis of the region with HAWC reveals a single point-like source characterized by a power-law (PL) spectrum. The *Fermi*-LAT analysis shows spatially extended gamma-ray emission that is coincident with the S106 region, while the archival Chandra X-ray observation reveals multiple unresolved point sources together with diffuse X-ray emission, which is best described by an absorbed power-law model.

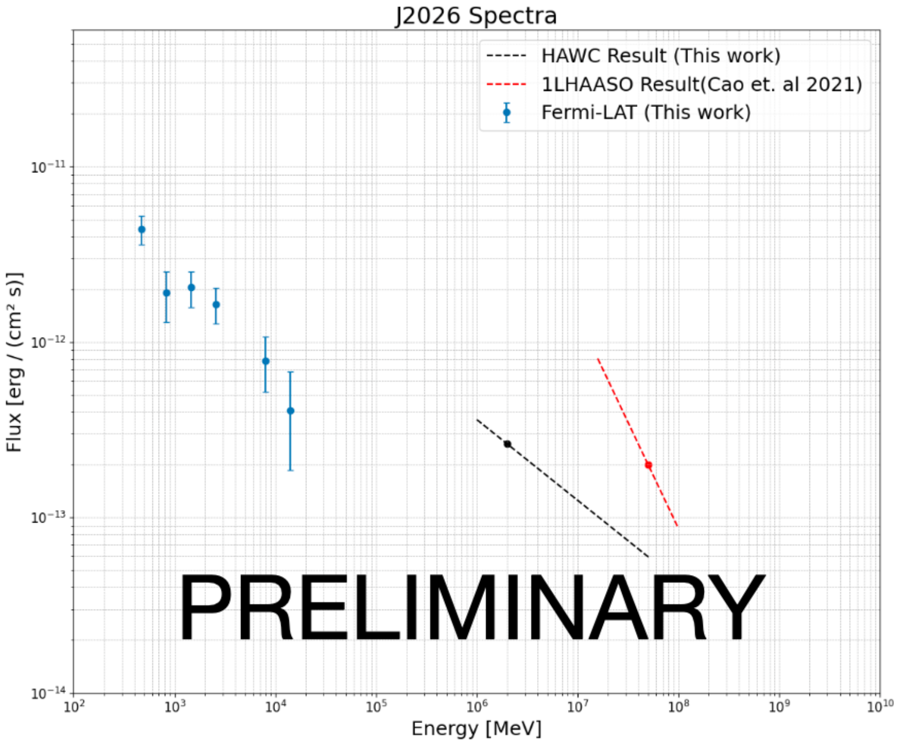


Figure 2: Spectrum of the sources found from HAWC (red) and *Fermi*-LAT (blue) analysis. LHAASO spectrum of J2027 is shown in red for comparison.

2.1 ^{12}CO Observations and Multi-Wavelength Spectrum

Fig. 1a shows the spatially extended Fermi-LAT emission surrounding 1LHAASO J2027+3657 after subtraction of all known background sources in the region, with the resulting Fermi-LAT significance contours overlaid. Fig. 1b presents the archival Chandra ACIS-I observation of the S106 region, revealing multiple unresolved point sources embedded within diffuse emission. Fig. 1c displays the HAWC excess map near the LHAASO source, with white contours indicating the Fermi-LAT emission. Fig. 1d shows the ^{12}CO molecular cloud distribution in the region from the DAME ^{12}CO survey. The best-fit HAWC source position is coincident with S106 and is slightly offset by $\sim 0.2^\circ$ from the reported LHAASO source location. The Fermi-LAT extended emission also overlaps with the dense molecular cloud region traced by the ^{12}CO DAME survey.

Fig. 2 shows the spectra of sources detected in the J2027 region, compared with the LHAASO measurements. The morphological similarities and spectral characteristics suggest a common origin for the observed emission. The presence of dense molecular clouds in the region, together with the TeV emission observed by HAWC, potentially indicates a local enhancement of cosmic rays, consistent with particle acceleration near the S106 region to TeV energies. The X-ray analysis shows that the emission in this region is consistent with a thermal plasma model, similar to that found in other star-forming regions.

3. Conclusion

In this contribution, we present a preliminary analysis of 1LHAASO J2027+3657 using HAWC, Fermi-LAT, and Chandra X-ray observations. This multi-wavelength study provides insight into the connection between the gamma-ray and X-ray emission and the S106 star-forming region, which is crucial for understanding potential cosmic-ray acceleration and gamma-ray production mechanisms in the region.

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