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Study of HESS J1857 with HAWC for a Multi-wavelength Analysis

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The High Energy Stereoscopic System (H.E.S.S.) collaboration reported the emission of two extended sources, HESS J1857+027 and HESS J1858+020, separated by $\sim 1°$, both lacking known counterparts. However, in the 3HWC catalog, the High-Altitude Water Cherenkov (HAWC) collaboration reported the emission of 3HWC J1857+027. We present a multi-source fitting analysis of the HESS J1857 region with ~2860 days of observations from the HAWC observatory as part of a multi-wavelength study effort to better understand the emission mechanisms of HESS J1857+026. With the improved performance and enriched statistics, we can now resolve the emission from both sources in the region beyond tens of TeV and observe a cutoff in the emission for J1857 for energies beyond ~30 TeV.

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1. Intro

The H.E.S.S. collaboration reported the emission of HESS J1857+026 (hereafter J1857) with a significance above 9σ for energies $E_\gamma \gtrsim 300$ GeV. J1857 was reported to have an extension of $0.11° \pm 0.08° \times 0.08° \pm 0.03°$ modeled with asymmetrical Gaussian model. J1857 lies 0.7° from HESS J1858+020 (hereafter J1858). Given this separation, and the absence of any connecting emission, the two sources were classified as distinct [1].

A follow-up campaign of observations from the ARECIBO observatory discovered a pulsar PSR J1856+0245 which had a period of 81 ms and characteristic spin-down age of 21 kiloyears (kyr) estimated to be at a distance of ~ 9.1 kiloparsec [2].

J1857 was also observed at GeV energies associated with 2FHL J1856.8+0256, with no clear pulsation signal from the pulsar [3, 4]. The MAGIC collaboration then performed a follow-up analysis using observations from July-October 2010 that added up to 29 hours of data. For energies above 1 TeV, they reported the detection of two sources, MAGIC J1857.2+0263 and MAGIC J1857.6+0297 with significances of 6.7σ and 6σ, respectively [5]. The MAGIC collaboration associated the emission of MAGIC J1857.2+0263 with that of PSR J1856+0245, but found a possible association with a HI region for MAGIC J1857.6+0297. A hadronic However, there was no positional coincidence observed with the densest regions of the cloud. They found the leptonic emission is preferred, but a hadronic contribution could not be ruled out.

In the H.E.S.S. galactic plane survey (HGPS), the extension of J1857 was reported with a significantly larger extension of $0.26° \pm 0.06°$ from the multi-component approach technique used in the survey [6]. Furthermore, in a recent work [7], the authors conducted radio continuum observations in search of the pulsar wind nebula and supernova remnant of PSR J1856+0245. Their study also used neutral hydrogen and molecular gas surveys to investigate the interstellar medium (ISM) properties within the vicinity of J1857. They report no observations associated with J1857 or PSR J1856+0245 at frequencies of 1.5 GHz and 6 GHz. The molecular gas maps show a cavity-like structure, suggesting the presence of a super bubble at a distance of ~5.5 kpc coinciding with the emission of J1857. The presence of the cavity structure and the extended nature of J1857 suggests that its emission is from a single source.

The HAWC collaboration reported the detection of the point source 3HWC J1857+027 with an offset of 0.14° from J1857 [8]. The current work uses a larger data set from HAWC as part of a multi-wavelength (MW) analysis effort to help uncover the emission mechanism for J1857.

2. HAWC

The High Altitude Water Cherenkov (HAWC) gamma-ray observatory is located on Sierra Negra Puebla, Mexico. The primary detector consists of 300 water Cherenkov detectors (WCDs) giving a total detection area of 22,000 m^2. Each WCD contains approximately 188,000 liters of ultra-purified water, equipped with four upward-facing photomultiplier tubes (PMTs) to detect Cherenkov radiation from secondary particles generated by extensive air showers (EAS). Thanks to its large detection area and high duty cycle > 95%, the HAWC observatory has a field of view of 2 steradians, which is optimal for the detection of extended gamma-ray sources.

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We report observations of J1857 using ~2860 days of *Pass 5* data from the HAWC observatory from June 2015 to January 2024 [9]. The current analysis uses the neural network (NN) energy estimator introduced in [10]. With the energy estimators, the HAWC data is now binned both in the fraction of PMTs triggered during an event and in true energy ($\hat{E}$) of quarter-decade width in $\log \Delta\hat{E}$ that extend from 0.316 to 316 TeV.

A multi-source fitting pipeline is now adopted for crowded regions along the Galactic plane, based on [11]. The evaluation of the best-fit parameters is carried out using the Multi-Mission Maximum Likelihood framework (3ML) [12], with the definition of test-statistic as

$$\mathrm{TS} = 2 \ln \frac{\mathcal{L}_{\mathrm{alt}}}{\mathcal{L}_{\mathrm{background}}} \tag{1}$$

where the $\ln \mathcal{L}_{\mathrm{alt}}$ represents the current best model, and $\ln \mathcal{L}_{\mathrm{background}}$ the previously accepted model. The pipeline consists of a systematic addition of sources into a model and a sequential comparison of TS between nested models. The pipeline is divided in point source addition and extension testing.

Firstly, a point source is added with a simple power law spectrum (SPL). The position, i.e., RA and Dec, and spectral parameters are free during the fit. The source is accepted as part of the model if the difference in TS is $\Delta\mathrm{TS} \geqslant 25$. The addition of point sources continues until the $\Delta\mathrm{TS} < 25$ between models.

The following is the extension test. The point sources accepted into the model are sequentially replaced by extended sources with a 2D symmetric Gaussian spatial shape in descending order of TS. A source is accepted as extended if $\Delta\mathrm{TS} \geqslant 16$, and assumed as point source otherwise. During this step, there are two additional cross-checks:

- Point sources with $\mathrm{TS} > 25$ are kept in the model and refit the entire model while floating all the parameters.
- Point sources with $\mathrm{TS} < 25$ are removed from the model. The model is fit again while floating all the parameters.

The above steps are carried until there are no more point sources untested.

The final segment of the pipeline is a curvature test in the spectrum for each of the sources. The curvature test is conducted similarly to the extension test. In this case, the spectral shape is changed from an SPL to a log-parabola for sources in descending order of TS. A source is accepted as having curvature if the $\Delta\mathrm{TS} \geqslant 16$. After all sources are tested, a final refit is performed to optimize the best-fit results.

For regions of interest away from the galactic plane, the above pipeline suffices. However, for regions along the galactic plane, it is important to take into account the diffuse background emission (DBE) from cosmic-rays or from unresolved source emission. In the current work, the DBE is modeled using the code from High-Energy Radiative MESsengers (HERMES) which models the gamma-ray (γ) emission of different physical processes. For the energy range of HAWC, the most dominant mechanisms are inverse Compton (IC) scattering from electron/positron cosmic-ray interactions with interstellar radiation fields, and neutral-pion (π^0) decay from hadronic cosmic-ray collisions with interstellar gas atoms [13]. After the diffuse emission from these mechanisms is estimated, a 3D template cube, intensity gamma-ray map projected in galactic or equatorial coordinates (see Figure 1) binned in energy from 0.1 to 1000 TeV is generated.

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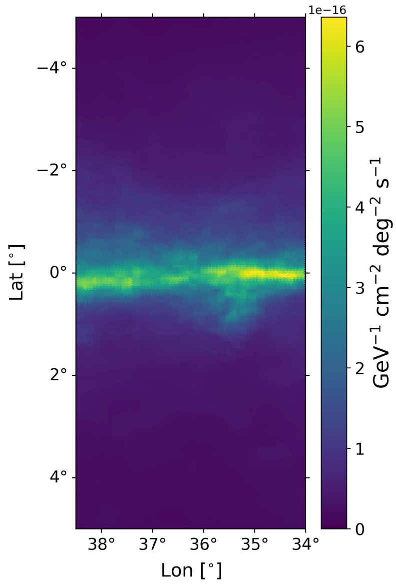

Figure 1: Hermes diffuse background emission template including diffuse emission from IC and π^0 decay.

3. Results

Figure 2 shows the emission for the J1857 region between energies of 0.316 to 316 TeV. In addition to J1857 and J1858 two other sources are reported using the multi-source methodology. Figure 3 shows the significance maps for the J1857 region at two energy ranges: 1 to 31.6 Tev and 31.6 to 316 TeV. For J1857, there is an evident cutoff in the emission from J1857 for energies above 30 TeV. The remaining emission $\geqslant 5\sigma$ coincides with J1858.

4. Discussion

This study presents the morphological and spectral study of J1857 using ~2860 days of *Pass 5* observations from the HAWC observatory. The results will be used as part of MW joint effort with observations from Fermi-LAT and VERITAS experiments to further constrain the physical mechanisms responsible for the γ-ray emission of J1857 in a forthcoming publication.

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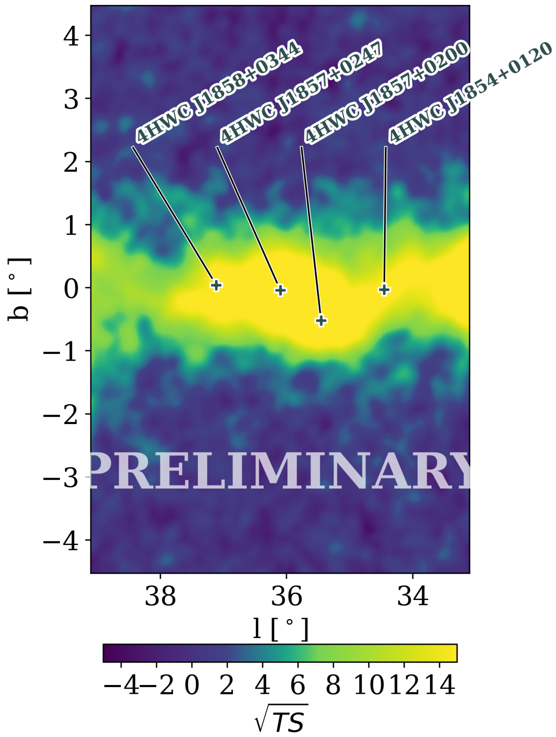

Figure 2: HESS J1857+026 region significance map smoothed with the HAWC point spread function.

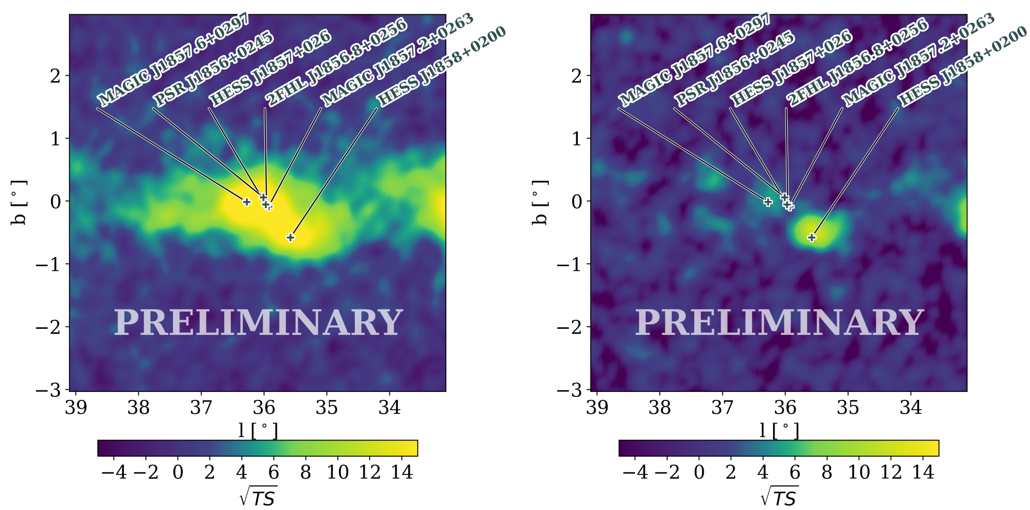

Figure 3: HAWC significance maps of the J1857 region at two energy ranges 1 to 31.6 TeV (*left*), and 31.6 to 316 TeV (*right*) smoothed with the HAWC point spread function. Both maps show source associations with J1857.

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