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Spectral Study of the West Jet Lobe of SS 433 with HAWC

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The High Altitude Water Cherenkov (HAWC) Observatory detected significant TeV gamma-ray emission from the jets of a microquasar, SS 433, in 2018. The gamma-ray emission from the powerful jets can reach up to a few tens of TeV, but the spectral studies at these energies have not been carried out. Compared to the east jet lobe, the west jet lobe is more challenging to analyze due to a higher level of contamination from nearby MGRO J1908+06 and the Galactic plane. With the most up-to-date HAWC data, the west jet lobe has over 8 sigma pre-trial significance. In this work, we use $\sim 1,922$ days of HAWC data to model the source confused region around the SS 433 west jet lobe and study its spectrum between 1 and over 200 TeV.

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1. Introduction

Discovered in 1977, SS 433 is the first source to have been labeled as a microquasar [1]. SS 433 is a binary system consisting of an unidentified compact object and a massive companion star. The compact object in the system accretes matter from the massive companion star. SS 433 is surrounded by a nebula called W50 that has been observed in radio [2]. The jets of SS 433 terminate inside of W50 from which two jet lobes, east and west, have been observed and studied in X-rays [3]. More recently, in 2018, these jet lobes have been observed to emit multi-TeV gamma rays by HAWC [4].

This discovery of the TeV gamma-ray jet lobes from HAWC has triggered a series of follow-up analyses from other experiments such as the the *Fermi* Large Area Telescope (*Fermi*-LAT) [5], Nuclear Spectroscopic Telescope Array (NuSTAR) [6] , and the High Energy Stereoscopic System (H.E.S.S.). However, most of these analyses are focused on the east jet lobe, which has left the SS 433 west lobe without new information.

Of the two lobes, the west jet lobe is more difficult to study due to its position. The west jet lobe is located closer to the Galactic equator, hence it is more susceptible to contamination from the Galactic diffuse emission. Furthermore, the west jet lobe is positioned right next to MGRO J1908+06, which has bright, extended emission that makes it more difficult for source analysis without considering the effects of MGRO J1908+06.

In this work, we present updated results on the SS 433 west lobe. Compared to [4], HAWC has accumulated almost double the amount of data. With 1,910 days of data, we have used a systematic source search to identify a TeV point source corresponding to the west jet lobe of SS 433. We also performed a spectral study for the west jet lobe between 1 and over 200 TeV.

2. HAWC

The High Altitude Water Cherenkov (HAWC) Observatory is a ground based particle sampling array that uses gamma-ray induced air shower particles to detect very-high-energy (VHE) gamma-ray photons. HAWC is located at a latitude of 19° N, at an altitude of 4.1 km next to Pico de Orizaba in Puebla, Mexico. The main detector array of HAWC consists of 300 water Cherenkov detectors (WCDs) that can cover a geometrical area of ~22,000 m^2. Each WCD is ~4.5 m in height and ~7.3 m in diameter and has a metal casing and a roof inside of which is a light-tight bladder filled with ~200,000 litres of purified water. Anchored to the bottom of each water tank are four photomultiplier tubes (PMTs) that are facing up towards the top. The PMTs will pick up any Cherenkov light produced by relativistic air shower particles.

By using the charge distribution and timing information of the PMTs, we can calculate the core position and the direction of the shower axis from which we can identify the position of the source of the primary particle as well as the primary particle type. We use simple topological cuts to discriminate between the hadronic cosmic ray showers and γ-ray induced air showers. A more detailed explanation of the event reconstruction can be found in [7]. Each reconstructed gamma-ray event is placed into an energy bin ranging from “a” to “l” for which the corresponding reconstructed energies vary between sources. The energy estimation process uses various parameters such as the fraction of the hit PMTs and the number of tanks hit by the shower. Currently, HAWC has two independent energy estimation algorithms, namely, the "ground parameter" (GP) and "neural network" (NN) energy estimators. In this work, we use the data generated with the NN energy estimator. For further information on the energy estimators, please refer to [8].

HAWC has an unbiased field of view of ~ 2 sr and > 95% duty cycle, which makes it ideal for observations of transient sources [9]. Also, the wide ~ 2 sr field of view allows for an effective multi-source and / or extended source analyses, hence source-confused regions can be studied adequately.

For a source analysis, HAWC uses test statistics (TS) as a measure of pre-trial statistical significance of a fitted model. The TS is used to determine how much an alternative hypothesis performs over a null hypothesis in a likelihood fit. The definition of TS is shown below:

$$\mathrm{TS} = 2\ln\left(\frac{L_1}{L_0}\right), \tag{1}$$

where L_0 and L_1 are the likelihoods for a null and alternative hypothesis, respectively. HAWC significance maps are also generated using the TS, where a one parameter (flux normalization) fit is performed for each pixel [10]. From Wilks' theorem [11], a pre-trial significance can be calculated using $\sigma \simeq \sqrt{\mathrm{TS}}$.

3. Analysis Method

In [4], we used prior information about the positions of the SS 433 jet lobes, adopting the known X-ray interaction regions "e1" and "w1" [3] for the east and west jet lobes, respectively. In this work, we have performed a blind search of the entire region of interest from which we have found three sources in agreement with [4].

For the systematic source search, a point source with a simple power-law spectral model is consecutively added to the nested model until the most significant excess within the ROI becomes less than 4σ. A simple power-law flux spectrum is given by:

$$\frac{dN}{dE} = K\left(\frac{E}{E_{\mathrm{piv}}}\right)^{-\gamma}, \tag{2}$$

where K is flux normalization at pivot energy E_{piv} and spectral index γ. Once the best model with point sources have been found, each of the point sources is replaced by an extended source model with a Gaussian spatial morphology starting with the most significant source. If the new model with an extended source model is improved by more than 4σ, we accept this model as the new best model. During this process, any of the point sources that are absorbed into an extended source is removed from the model. The Gaussian morphological model is given by:

$$\frac{dN}{d\Omega} = \left(\frac{180}{\pi}\right)^2 \frac{1}{2\pi\sigma_{\mathrm{G}}^2} \exp\left(-\frac{\theta^2}{2\sigma_{\mathrm{G}}^2}\right), \tag{3}$$

where θ is angular distance and σ_{G} is Gaussian width that represents the size of the fitted extended source in degrees.

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4. Results

Figure 1 (left) shows the significance map of the west lobe region produced using $\sim$ 1922 days of HAWC NN data. Figure 1 (right) shows the same region with the background sources subtracted using the best model found in Section 3. The new best-fit location is marked by the red cross, which is indeed located close to the jet interaction region "w1". On both plots, the black contours extracted from X-ray observations have been overlaid to compare the emission regions between X-rays and gamma rays.

Figure 2 shows the the flux data points of the west jet lobe produced from this work. The data points have been computed for each energy bin from c to l. The previous data point from [4] is also indicated in the plot. The two results are consistent within their uncertainties. The spectrum seems to follow a power-law like structure without any immediate signatures of a hard cutoff.

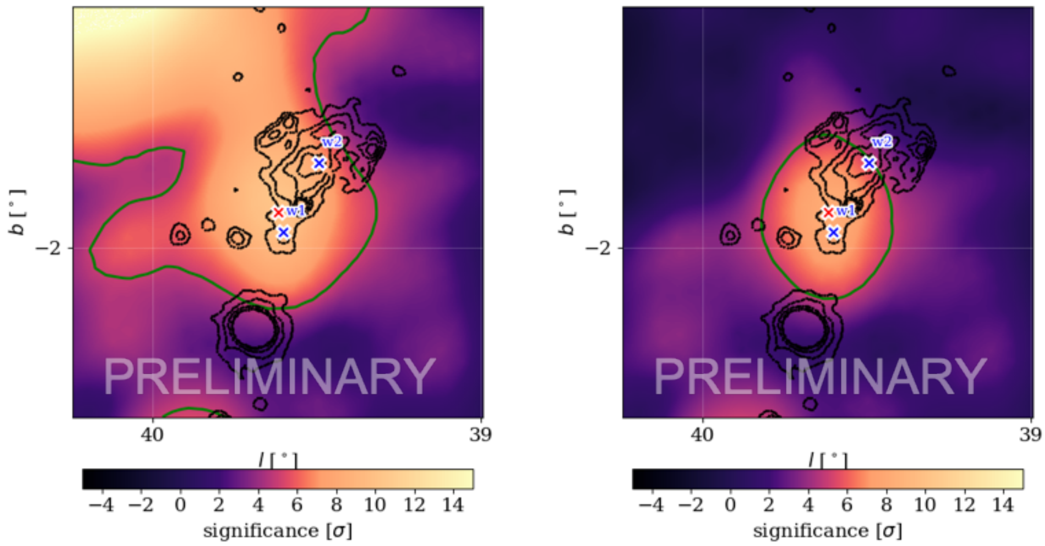

Figure 1: Left: The original significance map of the SS 433 region. **Right:** The residual map after subtracting the fitted MGRO J1908+06 model. On both cases, the green line indicates the 5σ contour on the HAWC significance map.

5. Conclusion

In this work, we have used 1,922 days of HAWC data to carry out a follow-up analysis on the TeV gamma-ray emission observed from the SS 433 west jet lobe. The systematic blind search has yielded the same number of sources as our previous assumption in [4]. Using a multi-source model, we have computed multiple flux points and upper limits across the TeV energy band for the west jet lobe, reaching over 100 TeV for the first time. By combining the computed HAWC data points with other multi-wavelength data, it would allow us to study the particle composition of the jet.

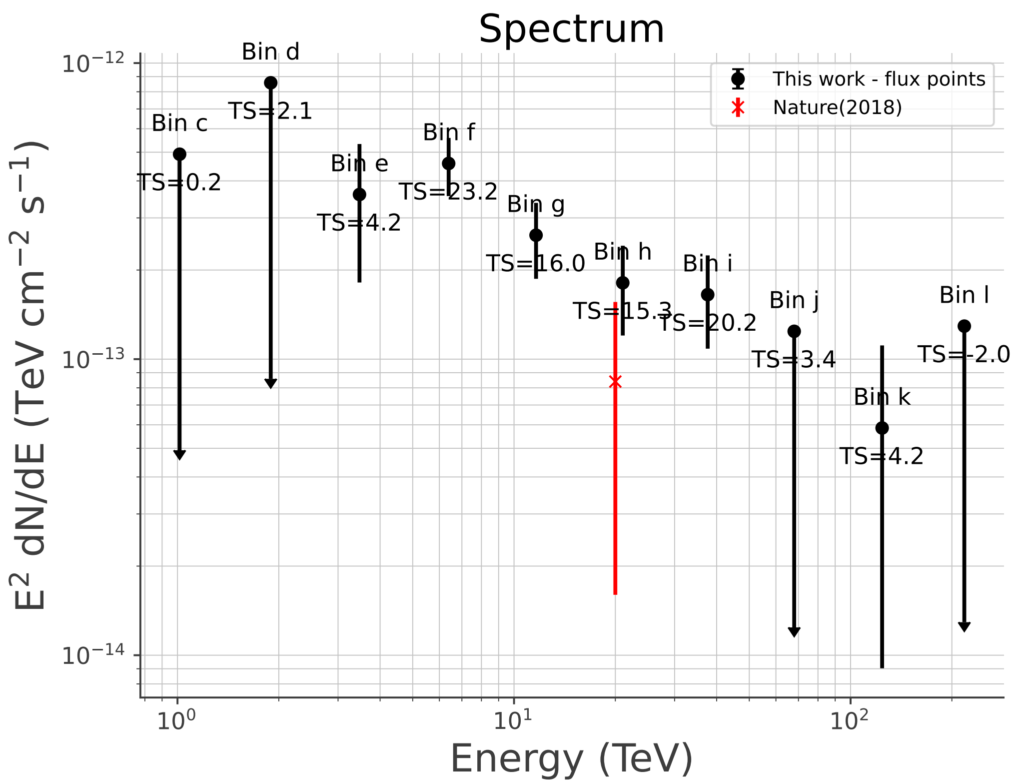

Figure 2: TeV flux points of the SS 433 west jet lobe from this work. The red star indicates the flux point from the previous work [4].

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