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MAGIC observations of HESS J1809-193 using the Very Large Zenith Angle technique at energies above TeV

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The origin of Galactic Cosmic rays (GCRs), whose spectrum extends to PeV energies, is one of the longest-standing problems in astroparticle physics. One of the main sources of GCRs are regarded to be Supernova remnants (SNRs). While SNRs are known to accelerate protons, so far there is no evidence that SNRs can accelerate CRs to PeV energies. Providing that 10% of the parent Cosmic ray energy is converted to gamma rays, the gamma-ray spectrum extending up to 100 TeV would be a signature of a so-called Galactic PeVatron, an object responsible for the production of protons up to the knee of the Cosmic ray spectrum. The current multi-wavelength data indicate that HESS J1809-193 is one of the most promising Galactic PeVatron candidates. So far, no firm identification on the source nature has been established as there are several possible counterparts at lower energies; one of them being SNR G11.00.0. We report here the results of an observational campaign performed by the MAGIC telescopes on HESS J1809-193 since 2019 in the very-high-energy gamma-ray domain (E>100 GeV). The data were obtained with the Very Large Zenith Angle (VLZA) technique, which increased the collection area significantly to about one square kilometer. We used 60 hours of collected VLZA data to explore the spectrum and the morphology of the source at energies above several TeV.

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1. Introduction

HESS J1809-193 was discovered during the systematic search for very-high-energy (VHE, E > 100 GeV) γ-radiation from pulsar wind nebulae in the Galactic plane survey performed by the H.E.S.S. Collaboration ([1]). The TeV emission of the source has an extension of $0.5° \times 0.25°$ with most of the emission concentrated in a $0.25°$ sub-region. The peak of the VHE emission lies about $6'$ to the south of PSR J1809-1917, a middle-aged (τ = 51 kyr) and energetic ($\dot{E} = 1.8 \times 10^{36} erg/s$) 82.7 ms radio pulsar. The source spectrum in the TeV range was fit with a power-law with a spectral index of 2.2. Using radio data from the Karl G. Jansky Very Large Array, a search for the counterpart to the predicted pulsar wind nebula (PWN) generated by PSR J1809-1917 was recently conducted, but no such counterpart was identified. In the analysis by [2], multiple molecular clouds were discovered at the shock front of the SNR G11.0-0.0 with the location of molecular clouds coinciding with the peak of the TeV gamma-rays. The analysis also revealed evidence for interaction between the SNR and the clouds. According to [2], the distance between the SNR and the clouds is 3 kpc. As a result, the authors hypothesized that hadronic interactions can explain the gamma-ray emission.

In the regions of HESS J1809-193, [3] reports the discovery of extended emission in the 0.5-500 GeV range. The emission has a simple power-law spectrum with a spectral index of $\Gamma \sim 2.2$, which is similar to that of the TeV source. This is difficult to explain with IC emission from high-energy electrons alone, implying that the emission is hadronic. The hadronic scenario for HESS J1809-193 necessitates a proton spectrum ranging up to 1 PeV. However, a deeper measurement of the spectrum at tens of TeVs is required to confirm its hadronic nature. Other scenarios involving combinations of leptonic and hadronic emission from several known SNRs in the region cannot be ruled out yet.

The notion that HESS J1809-193 is accelerating protons to PeV energy could be important to cosmic ray origin theories. Although the current paradigm for cosmic ray origins implies that SNRs operate as PeVatrons for at least part of their evolution, no known SNR has a gamma-ray spectra that supports this theory. The confirmation of cosmic ray acceleration to PeV energies in the HESS J1809-193/G11.0-0.0 system would be a significant step forward in our knowledge of cosmic ray origins.

2. Very Large Zenith Observations

The detection of astrophysical sources at multi-TeV energies may shed light on the mechanism of particle acceleration at the highest energies. In case of Imaging Air Cherenkov Telescopes (IACTs) this requires very long observation times or very large detector arrays, like the upcoming Cherenkov Telescope Array (CTA). The MAGIC Collaboration developed a method for observations at Very Large Zenith Angles (VLZA) [4] by observing above ~60° zenith, thereby increasing the collections area to $\sim km^2$. Observing in VLZA regime rises the energy threshold to several TeV, which limits the telescope sensitivity to the highest energies.

3. MAGIC Observations and Datataking

The MAGIC (Major Atmospheric Gamma Imaging Cherekov) telescopes are two 17m diameter IACTs. They are located on the Canary Island of La Palma (Spain) at the Roque de los Muchachos

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Observatory at 2200 m above sea level. The telescopes record images of extensive air showers (EAS) in stereoscopic mode and perform observations of VHE gamma-ray sources [5].

The data sample used in this analysis had been accumulated since 2019 in the zenith angle range 50° - 80° totalling ≃ 60 hr of good-quality data taken during dark time after the initial data cleaning. The observations were performed in wobble-mode [6] at symmetrical positions away from the central sky position, which allowed a simultaneous background estimation. The data was taken with wobble offsets of 0.4° and 0.6°. Diffuse Monte Carlo (MC) data was used to simulate the telescope performance. The MCs had been generated in a way that the events were randomly distributed between 0 and 2.5° from the camera center, thus simulating an extended source.

4. Data Analysis

The collected data was analyzed with standard MAGIC Analysis and Reconstruction Software (MARS) [7]. Events taken during bad weather conditions were discarded. In this case, data taken during median of the aerosol transparency measurements relative to that of an optimal night lower than 0.8 was discarded [8]. In addition to that, a cut on the number of stars visible in the field of view (FoV) of the auxiliary pointing cameras was applied. Standard MARS routines were used to reconstruct the incoming direction, energy and to classify the initiating particles of the extended air showers.

For extended source analysis, a spatial likelihood analysis tool for MAGIC telescope data called SkyPrism [9] was used. The SkyPrism analysis package enables a proper reconstruction of extended sources fluxes over the entire FoV, as the accuracy of the SkyPrism analysis does not degrade with the off-set from the telescope camera centre. SkyPrism uses a 2D spatial modelling (3D if energy is considered) of the measured sky signal. Applying the instrument response to an assumed source model, it can generate an image of the model as it would be seen by the telescope. This model, along with the estimated background map, is fitted to the measured sky image to estimate the most likely flux of the model sources in the chosen sky region.

The chosen method to reconstruct a background exposure model was the so called "Exclusion Map". Using this approach the source itself was excluded in the construction of the background map. Typical selection cuts with 80% efficiency, based on the MCs, for γ-ray/hadron separation were used. After the applied analysis cuts the resulting energy threshold of the VLZA dataset was found to be ~2.5 TeV. We performed a test-statistic (TS) scan in order to find the source best fit position and extension. The spatial models used were: pointlike, symmetric 2D Gaussian and a disk. As for the spectrum, we tested the power-law, power-law cutoff and log-parabola source models. Background was chosen to be isotropic with a log parabola cutoff spectrum.

5. Results

Figure 1 shows the relative flux map as seen by MAGIC compared to recent HAWC measurements [10]. eHWC J1809-193 has similar position and flux to that of the measured MAGIC results. eHWC J1809-193 has measured extension of $R_{68} = 0.51° \pm 0.19°$ and position within the uncertainty of MAGIC extension of $R_{68} = 0.23° \pm 0.07°$. A maximum likelihood scan was performed to obtain the source location and extension with Point Source, Disk and 2D symmetric

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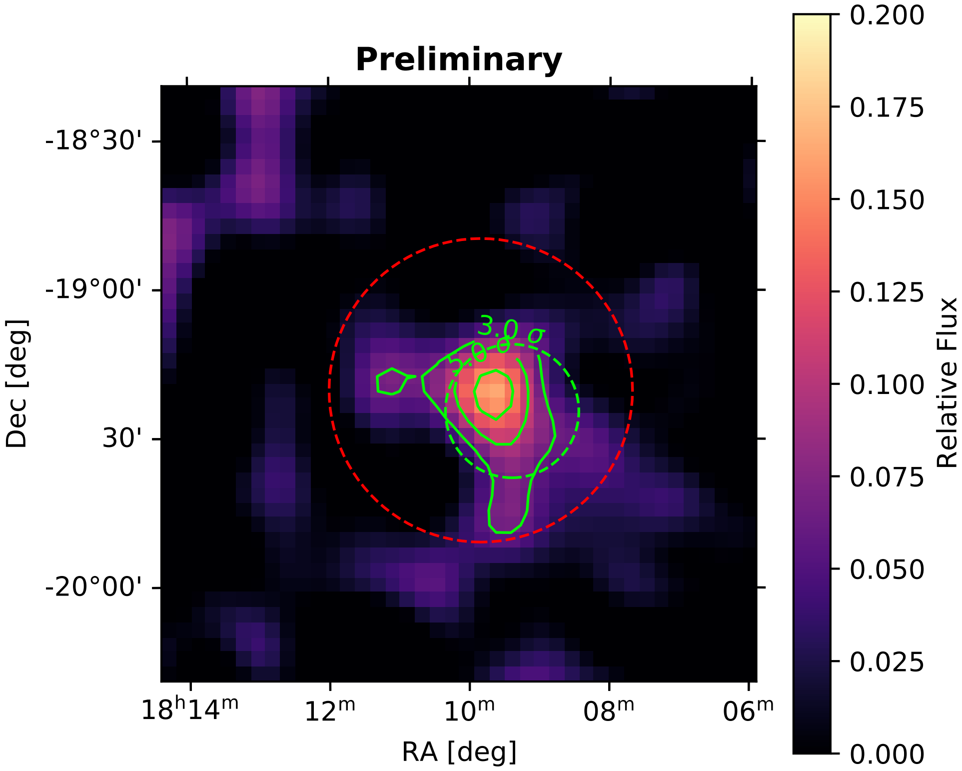

Figure 1: The relative flux skymap of HESS J1809-193 as seen by MAGIC. The skymap covers 3 TeV to 400 TeV in estimated energy. The green dotted circle represents the R_{68} from the morphology study. The green solid lines represent the 3σ, 5σ, and 7σ contours. The red dashed line is the R_{68} of eHWC J1809-193 [10]

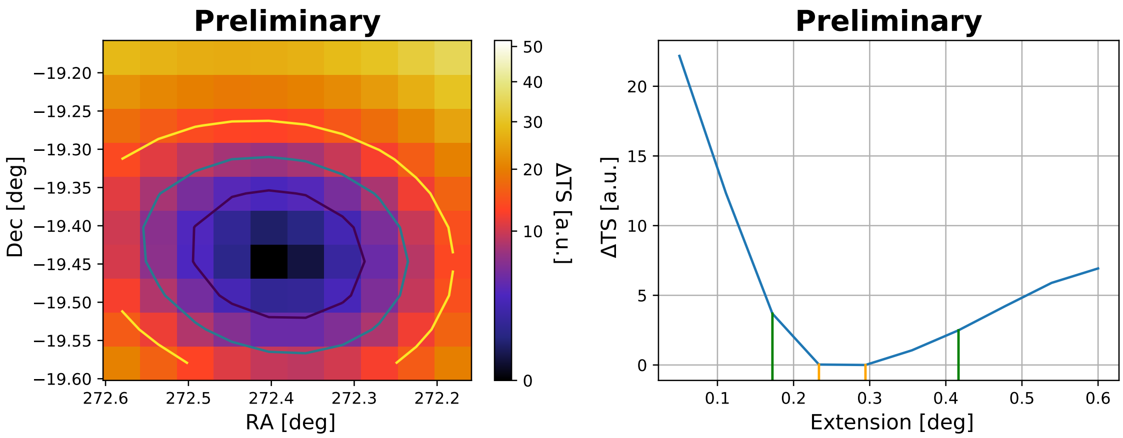

Figure 2: The plots display the results of the TS map scan for the best value for the Ra, Dec and extension using the MAGIC data based on the radially symmetric Gaussian source model. The contours for the 2D plot represent the 1σ (purple), 2σ (blue), 3σ (yellow) errors from this this scan, while for the 1D plots the vertical lines represent the 1σ (yellow) and 2σ (green) errors from this scan.

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Gaussian as input source models used in the scan. A likelihood ratio test was performed between the point source and the extended models and the 2D symmetric Gaussian spatial model provided the best likelihood value overall. The parameter distribution for the localisation and extension tests of 2D symmetric Gaussian is shown in Figure 2.

For the spectral analysis we used the best spatial model for estimating the spectral parameters. From the forward folding results the Power Law with Exponential Cutoff and Log Parabola were both preferred over a Power Law at about 5σ level. The resulting data was then used for the joint forward-folding fit together with Fermi-LAT data and again the Power Law with Exponential Cutoff was preferred over the Power Law. The obtained results are most in line with the recent HAWC measurements [10], which is expected considering the similar extraction region and energy range.

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