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Follow-up Analysis to Geminga's Contribution to the Local Positron Excess with the HAWC gamma-ray Observatory

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Two cosmic-ray experiments, PAMELA and AMS-02, measured an abnormal positron excess above 10 GeV. This excess is well understood, but it has been considered direct evidence of dark matter. However, this excess could be produced by nearby pulsars too. The HAWC collaboration previously studied the extended gamma-ray emission of two nearby pulsars, Geminga and PSR B0656+14, but found no significant contribution to this excess from these pulsars. The previous study of HAWC led to the reinterpretation of our result and initiated the concept of inverse Compton (IC) halos. Fitting a new halo model and 1343 days of data from the HAWC gamma-ray observatory may better constrain the contribution of these pulsars to the positron excess. This halo model utilizes 3D templates of gamma-ray emission from electron IC interactions to fit the diffusion coefficient and electron injection spectral index. This model can further help to study the energy-dependent diffusion and incorporate anisotropic diffusion with the proper motion of the pulsar.

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1. Introduction

Pulsar wind nebulae are considered natural sites of efficient electron and positron emission with particle acceleration powered by the pulsar or surrounding nebulae. Their e^-e^+ emission is estimated to contribute largely to the leptonic Galactic cosmic ray flux. This contribution could help explain observations of an excess in the positron fraction above an energy of 10 GeV measured by PAMELA [1], Fermi-LAT [2], AMS-02 [3]. The nature of the mechanism responsible for this anomalous excess is not well understood. However, work from several people suggests the origin of this excess is a consequence of dark matter particle mechanisms: annihilation/decay or nearby astrophysical sources–pulsar wind nebulae[4][5].

The HAWC collaboration reported the first observations of two extended gamma-ray regions coinciding with the sky locations of two middle-aged pulsars, Geminga and PSR B0656+14 (Monogem) [6]. These two sources were candidates for the study of their contribution to the local positron excess. The extended gamma-ray emission was associated with inverse Compton (IC) interactions as e^-e^+ escaped into the interstellar medium via diffusion. The HAWC collaboration presented a spectral and spatial study of Geminga and Monogem with 500 days of data. The results demonstrated high efficiency in conversion of pulsar spin-down energy to e^-e^+ emission but derived a diffusion coefficient that was 100 times smaller than the average galactic value. This result suggests that if such a slow diffusion region extends to Earth, then any e^-e^+ emission from Geminga and Monogem is insufficient to explain this abnormal positron excess [7].

This study introduced a new class of gamma-ray sources referred to as “TeV halos". TeV halos differ from pulsar wind nebulae as they can extend up to a few tens of parsecs [8]. The extended gamma-ray regions result from e^-e^+ IC interactions with low energy fields as they escape into the interstellar medium (ISM) via diffusion. Work from [9] at GeV energies with Fermi-LAT observed the halos around Geminga and Monogem and confirmed the presence of a slow diffusion region up to 100 parsecs. The recent observations from [10] measured region slow diffusion at $\sim$ 160 TeV region for halo around PSR J0622+3749 which claims slow diffusion is a property of TeV halos.

This contribution discusses a new halo model for studying two TeV halos, Geminga and Monogem, with the HAWC observatory. The new halo model permits the study of the diffusion coefficient, injection spectral index, and efficiency of pulsar spin-down energy to e^-e^+ emission. This model was used on a 1343 day HAWC data set, which shows an improvement over the result from HAWC.

2. Model

This model utilizes three-dimensional templates of diffuse gamma-ray emission from inverse Compton (IC) interactions with spectral and spatial information for a pulsar. Each pixel in this template contains values with units of flux 1/(MeV cm^2 s sr) for different energy bins in the range of 100 GeV - 100 TeV. The templates use flux estimates from [9] for different injection electron/positron spectral indices and diffusion coefficients (see Figure 1). The efficiency in conversion of pulsar spin-down energy to e^-e^+, $K(\dot{E} \rightarrow e^-e^+)$ is assumed to be 100%.

We investigated the effect of diffusion coefficient on the spectra of the gamma-ray emission, which required one-dimensional spectral templates with fluxes integrated for different regions

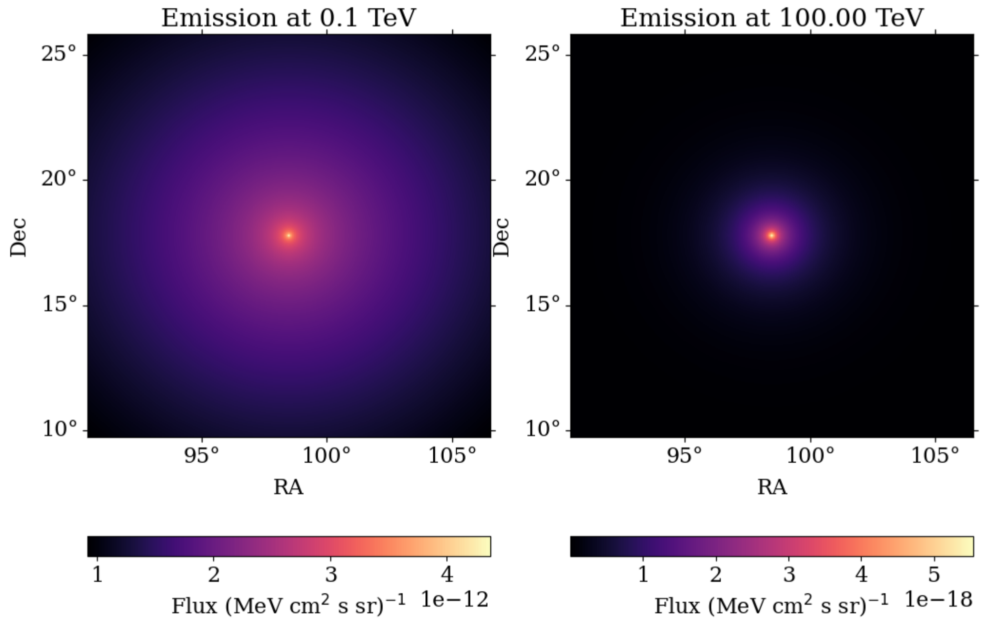


Figure 1: Templates of gamma-ray emission with a diffusion coefficient D_0 = 1.58 cm^2/s at 1 GeV for a injection spectral index of 2.0. The region of gamma-ray emission at 0.1 TeV shows a larger extent than at 100 TeV because of the significant e^-e^+ energy losses.

around the pulsar. This effect showed that high diffusion coefficients require large regions for full containment of gamma-ray emission, which reflected flux values differing by almost an order of magnitude. The impact on the gamma-ray spectra became negligible for a region of 20-30 degrees. With this study, it was possible to separate the relationship between diffusion coefficient and injection spectral index. Furthermore, the flux values for a region of the 30-degree region were used to normalize the 3D template pixel values, leaving them with 1/(sr) units.

We propose a new halo model that builds a table of 3D normalized templates, which permits the interpolation over different diffusion coefficients and injection spectral indices over normalized flux values. The interpolated values are further interpolated over the template parameters: energy, RA, and Dec. The fitting parameters for the analysis are then diffusion coefficient, injection spectral index, and $K(\dot{E} \to e^-e^+)$. The above model provides a custom spatial shape to study the morphology of TeV halo candidates with a custom spectral shape from the aforementioned spectral templates.

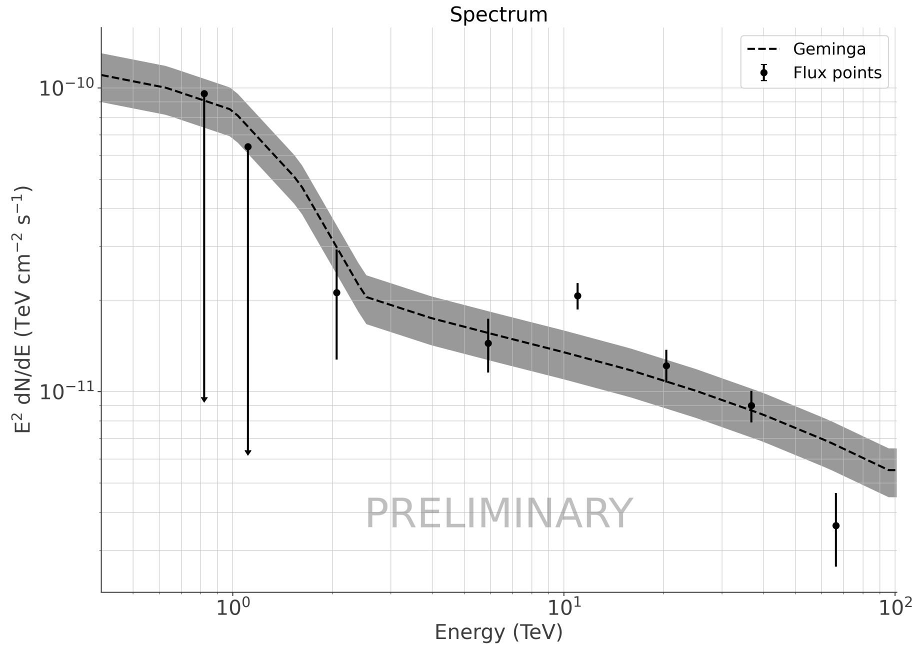


Figure 2: Geminga spectrum obtained with implemented halo model. First flux points show rescaled flux values from 30-degree region to a 8-degree region. Change in slope $\sim$ 2 TeV is a consequence of continuous injection that becomes important above this energy. The fitting parameters for Geminga are diffusion coefficient, spectral index, and $K(\dot{E} \to e^- e^+)$. The gray band shows the statistical errors from the analysis.

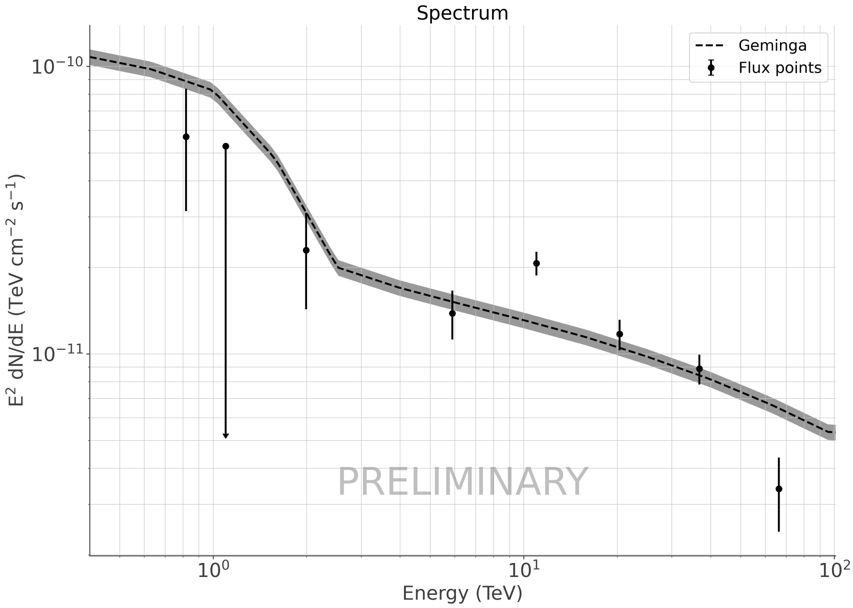
3. High Altitude Water Cherenkov Observatory

The HAWC gamma-ray observatory is on Sierra Negra Volcano at an elevation of 4,100 meters in Puebla State, Mexico. The HAWC site houses 300 water Cherenkov detectors (WCDs), each with dimensions 7.3 meters in diameter and 5 meters in height. A WCD holds up to 220,000 liters of ultra-purified water with four photomultipliers at its base that detect Cherenkov light emitted by charged particles from air showers. HAWC has an effective area of detection of 22,000 m^2, which grants a field of view of 2π and can observe 2/3 of the northern sky with a $> 95\%$ duty cycle.

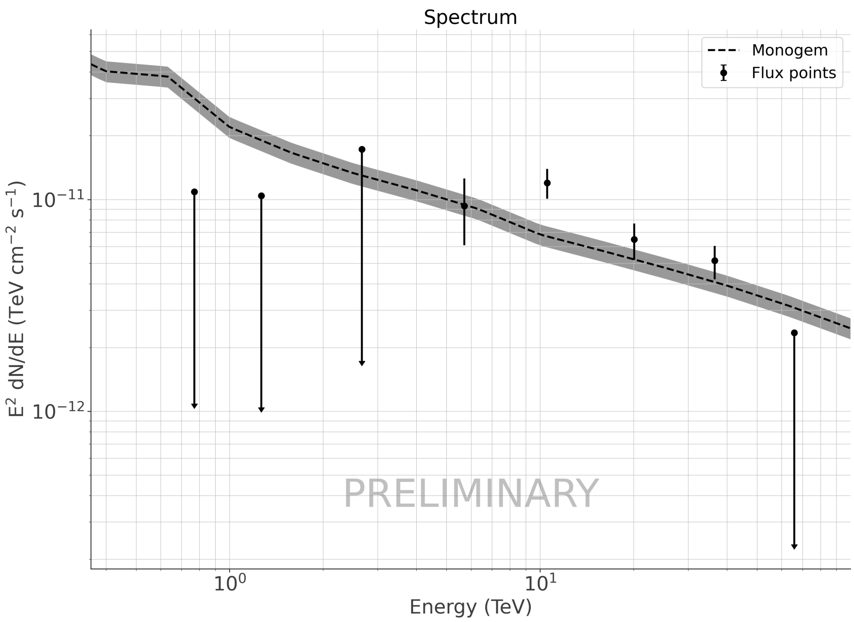
The wide field of view of HAWC makes it the ideal instrument to study extended sources like Geminga and Monogem. The first derived result for diffusion coefficient was obtained with 500 days of data after its full operational deployment in March 2015, with data binned by the fraction of the detector hit during the event. We report the first preliminary results from a newly implemented TeV halo model on the halos around of Geminga and Monogem with 1343 days of HAWC data that use the ground parameter technique [11].

4. Results & Discussion

The analysis used the halo model with templates for diffusion coefficients of $10^{25} - 10^{28}$ cm^2/s at 1 GeV and spectral indices of 1.5 - 2.4. This range allowed for thorough sampling of the fitting parameters. The resulting spectrum for Geminga is shown in Figure 2.



(a) Geminga



(b) Monogem

Figure 3: Joint fit of Geminga and Monogem using the halo interpolation model. The diffusion coefficient and spectral index for both sources were fixed to the best-fit results from the Geminga only analysis. The only fitting parameters are the $K(\dot{E} \rightarrow e^- e^+)$ for Geminga and Monogem.

The first feature to notice is the upper limits for energies $\sim$ 1 TeV. These flux values are not "true" detections by HAWC, but as mentioned in section 2, large diffusion coefficients require large regions to contain diffuse gamma-ray emission fully. Therefore, these flux values are rescaled from a 30-degree region to that of 8 degrees. Secondly, a change in slope at $\sim$ 2 TeV is a consequence of continuous diffuse injection that becomes important above the maximum energy of the source under a burst-like assumption. This value can be calculated by

$$\varepsilon_{source,max} = \frac{1}{b \cdot t_{age}}, \tag{1}$$

where b represents the e^-e^+ sources and t_{age} is the age of the source. This change in slope is typical of positron spectra, but it shows at comparable energies in gamma-ray spectra because of the large energy losses that e^-e^+ as they diffuse through the ISM.

The best-fitting results are presented at the conference but show good agreement with the derived diffusion coefficient by the HAWC collaboration. The diffusion coefficient and spectral index values obtained from Geminga were assumed for the combined fit, including Monogem. The spectra for both sources assuming with the halo model are shown in Figure 3. The spectral shape for TeV energy ranges shows a preference in curvature for both Geminga and Monogem.

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