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Gamma Ray Diffuse Emission from the Galactic Plane with HAWC Data

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The Galactic γ-ray diffuse emission is produced by the interaction of cosmic rays (CRs) with ambient gas and radiation fields. Studying this radiation helps us to reconstruct particle transport and distribution in the Galaxy. We will present the analysis of HAWC (High Altitude Water-Cherenkov) data to measure the spectrum and the angular distribution of the diffuse emission from the Galactic Plane. In the future, we will use these HAWC measurements to constrain particle transport properties in different regions of the Galactic Plane, such as close to the Galactic Centre, comparing them to the predictions of transport models implemented with the DRAGON code, which solves the CR transport equation in the Galaxy under general conditions including inhomogeneous and anisotropic diffusion. In particular, we use HAWC results to scrutiny a model based on inhomogeneous diffusion which - better than conventional models - provides a good description of the diffuse emission measured by Fermi-LAT and Milagro along the inner Galactic plane and in the Galactic center region.

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1. Introduction

Cosmic rays (CRs) are the highly energetic hadrons and electrons which fill the Galaxy and carry on average as much energy per unit volume as the gas, and the magnetic and radiation fields. CR secondary data suggest that cosmic protons and nuclei diffuse in the magnetic fields for a timescale of the order of 10^7 years before escaping the Galaxy. During propagation, the particles accelerated by individual sources loose the directional memory of their origin, and redistribute diffusively in the Galaxy contributing to the bulk of Galactic cosmic rays known as cosmic ray background. Below PeV energies, the CR spectrum measured close to the Earth approximately follows a power-law with a soft index between -2.7 and -2.8 spectrum [1], which is usually assumed to be representative of the CR spectral index throughout the whole Galaxy.
The Galactic diffuse γ-ray emission originates from the interactions of background CRs (hadrons and electrons) with the matter and radiation fields in the Galaxy. CR hadrons interact with matter producing neutral pions (π^0) which in turn decay into γ-rays while CR electrons produce high-energy γ-rays by inverse Compton (IC) scattering off the interstellar radiation fields. The main motivation for studying the angular and spectral features of the diffuse γ-ray emission from the Galactic disk is that it can provide a valuable probe of the CR background spectrum and distribution in different locations of the Galaxy and can help constraining their transport properties. The diffuse emission of the Galaxy has been up to now mostly investigated with detectors such as EGRET[1] and Fermi LAT[2] orbital telescopes in the MeV-GeV energy range, and with Milagro[3] and HAWC in TeV and multi-TeV energy range. While at GeV energies the Galactic diffuse emission is dominant over other contributions, at TeV energies the sky is dominated by point-like source emission while the diffuse emission from background cosmic rays becomes faint and difficult to detected. As a matter of fact a major difficulty when measuring diffuse emission is to identify the truly diffuse γ-ray emission from the contribution of weak unresolved sources.
Here the HAWC measurement of the diffuse emission (which is an upper limit of diffuse emission due to the contribution of unresolved sources) above 1 TeV from a region of the Galactic plane of longitudes $l \in [30^\circ, 85^\circ]$ and latitudes $b \in [-4^\circ, 4^\circ]$ is presented. Furthermore, the measured γ-ray flux and the latitudinal and longitudinal profiles of the emission are compared to predictions of two reference CR propagation models implemented with the DRAGON package [2, 3].

2. Analysis

2.1 HAWC

The High-Altitude Water Cherenkov Gamma-Ray (HAWC) Observatory [4] is well-designed to study CRs and γ-rays with energy between 300 GeV and beyond 100 TeV by detecting the air-shower particles created by the primary particles in the high atmosphere which get to the detector. The HAWC observatory is located on the side of the Sierra Negra volcano near Puebla, Mexico at an altitude of 4,100 meters.
Thanks to its large field-of-view, HAWC observes two thirds of the sky daily. A data set accumulated over 1128 days by HAWC from 2014 to 2018 were analyzed (figure 1) using the Multi-Mission Maximum Likelihood (3ML) framework[4].

2.2 Analysis on the Galactic Plane

Our study of diffuse emission is focused on a region of interest (ROI) in between 30° and 85° in Galactic longitude and $-4°$ and $4°$ in Galactic latitude. The selected region is considered to probe the γ-ray Galactic diffuse emission (GDE) with HAWC data at energy range above 1 TeV. A maximum likelihood fit of the HAWC data to an assumed model of the region including point sources, extended sources, and GDE signals is performed.

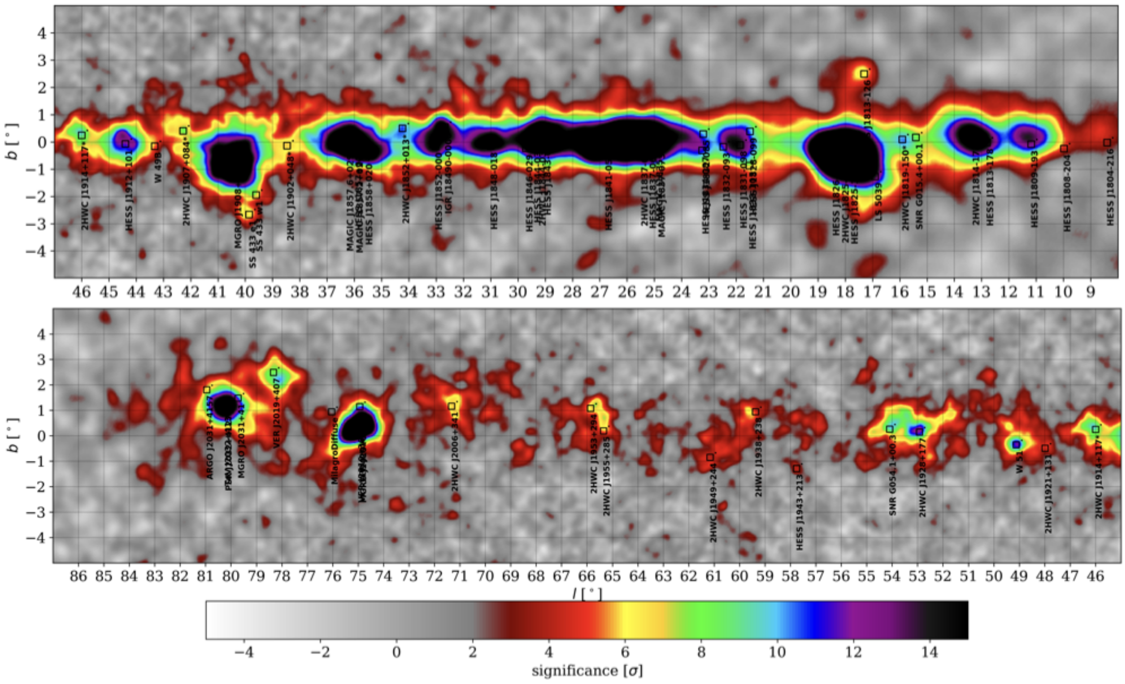

Figure 1: HAWC significance map of inner Galactic Plane in Galactic coordinates.

Our model assumes a Gaussian morphology for the extended sources and a simple power law (SPL) as energy distribution for all sources:

$$\frac{dN}{dE} = I_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \tag{2.1}$$

where Γ and I_0 are the spectral index and flux normalisation respectively. The GDE model template are obtained from DRAGON [2, 3]. The GDE is in the model an extended source in b $< |4|$. DRAGON is a code that solves the particle transport equations to find the large scale distribution and the point-by-point energy spectrum of the CR background. The CR background spectrum is then integrated along the line of sight with the gas distribution and hadron scattering cross-section to get a simulated map and spectrum of the γ-ray diffuse emission. That includes the contribution of neutral pion decay (π^0), Inverse Compton scattering (IC), and deceleration radiation (bremsstrahlung). Here we consider two reference models for the GDE; the *base* and *gamma* models. The former is a conventional model assuming the same spectral CR index in the whole Galaxy while the latter [6, 7], which was built to account for the excess found by Fermi in inner Galactic plane [8], assumes a spatial dependent diffusion coefficient predicting a progressive hardening of the CR spectrum for a decreasing Galactocentric radius which was confirmed by the Fermi-LAT collaboration [9].

3. Results

The starting point of our analysis are the HAWC maps from the Galactic Plane in Fig.1. Fitting all sources with a significance higher than 6 sigma, sources reported in 2HWC catalog as well as some sources reported in TevCat[5] and subtract them from the HAWC map we obtain the significance maps in Figure 3.

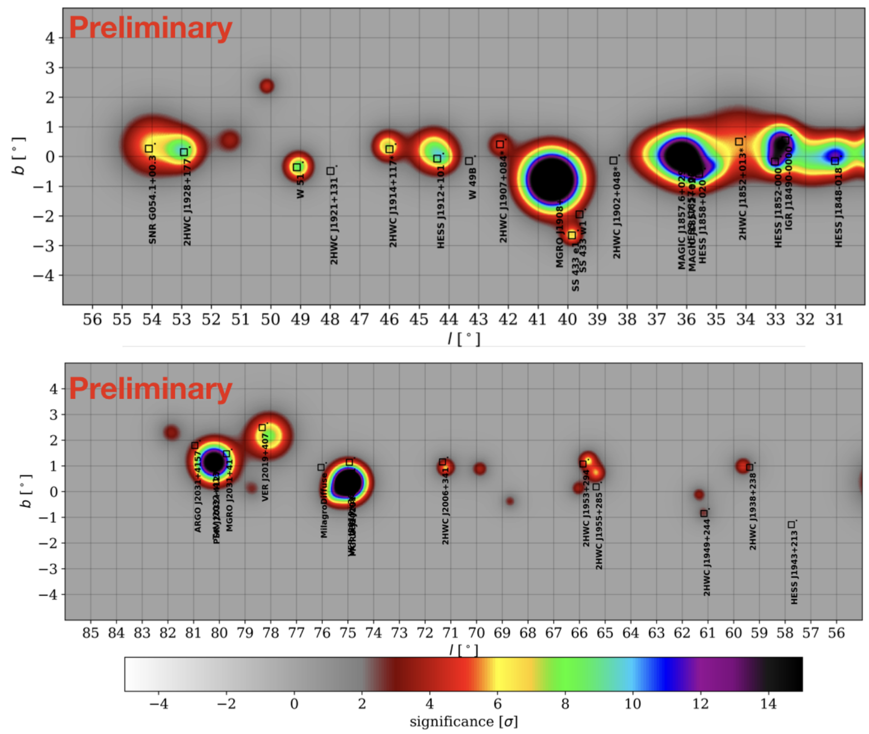

Figure 2: Model map of the galactic plane seen by HAWC.

Figure 3 shows the significance map of the residual after excluding the known sources. Latitude and longitude profiles of the source subtracted map were studied to investigate diffuse emission in the Galactic plane (Important caveat to the analysis is that for now, we use simplified models to describe point and extended sources. Some of these regions are currently being investigated inside the HAWC collaboration and better modeling for some of them will be obtained after the analyses are done).

As it is shown in figure 3, the intensity of GDE (and likely unresolved sources) increases in the direction of the center of the Galaxy, and also in the more populated regions.

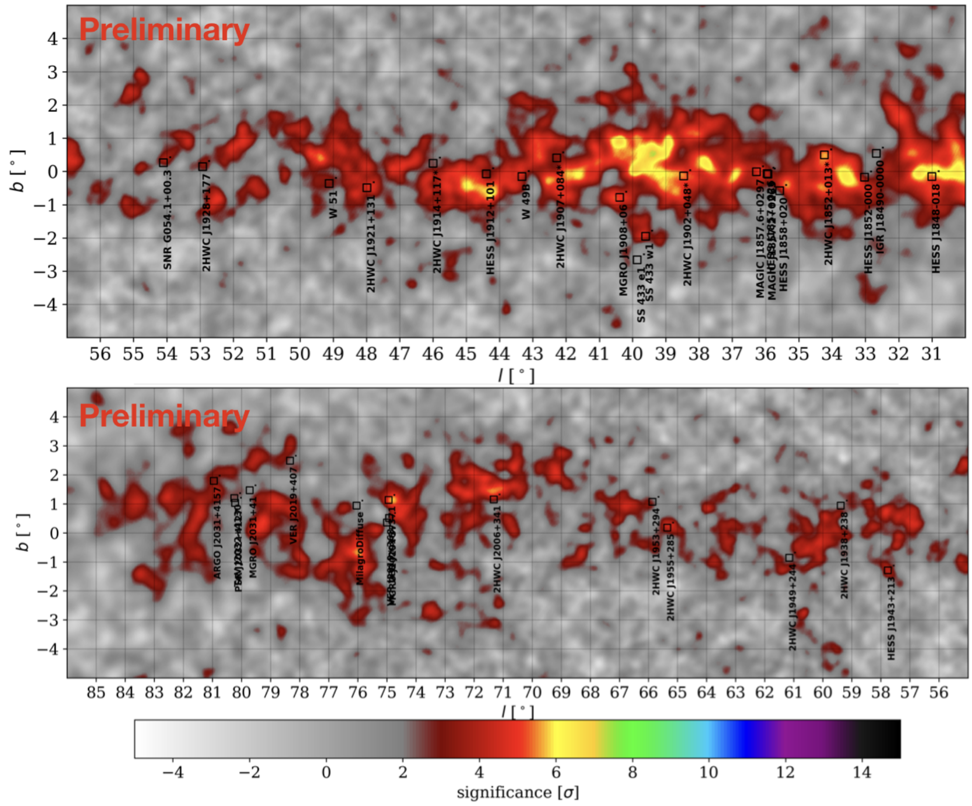

Figure 3: Residual significance map.

3.1 Longitude and Latitude Profile

The longitude profile of the GDE is represented in figure 4 for b $<$ $|2|$ over the Galactic Plane. The blue line represents the diffuse emission measured by HAWC (and a contribution of unresolved sources), while the red and green lines are the DRAGON *base* and γ *model* predictions respectively.

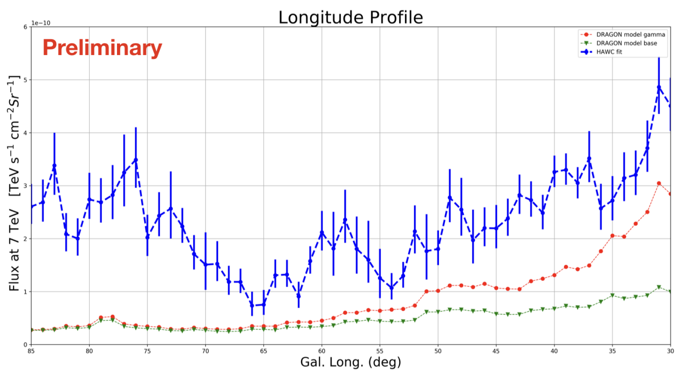

Figure 4: Galactic Longitude profile at 7 TeV.

The latitude profile of the GDE is also produced for b< |4| (figure 5) for two different regions, between $l \in [30°, 65°]$ and $l \in [65°, 85°]$ as well as the GP $l \in [30°, 85°]$. As expected flux reaches the maximum at b=0° in the region within $(30° - 65°)$ as well as region $(30° - 85°)$, but it has a maximum at $b = 1°$ within the region $(65° - 85°)$.

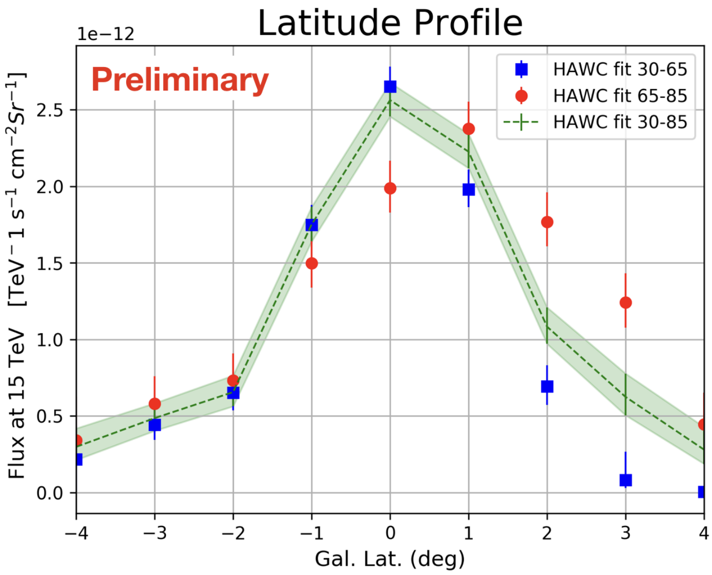

Figure 5: Latitude profile at 15 TeV

3.2 Comparison with Milagro

In figure 6 we represent the γ-ray emission measured by HAWC and Milagro [5] at 15 TeV in a region within b< |2|. Comparing the flux of the diffuse emission measured by HAWC and Milagro shows a higher statistical significance and lower diffuse flux by HAWC data respect to Milagro.

Region for $b < \|2\|$	Milagro		HAWC		
	Statistical Significance	Diffuse Flux	Statistical Significance	Diffuse Flux	
l : (deg)	σ	F^*_{15}	σ	F^*_{15}	Index
30 – 65	5.1	23.1	29.36	13.85	-2.59
65 – 85	8.6	21.8	18.32	13.82	-2.51

Figure 6: GDE from GP at 15 TeV measured by HAWC and Milagro ($\times 10^{-13} TeV^{-1} cm^{-2} s^{-1} sr^{-1}$).

The measurements in the table should be considered as upper limits to the GDE due to the unresolved sources

3.3 Gamma-Ray diffuse emission excess

The measured GDE is the result of unresolved sources and true emission from background cosmic rays nuclei and electrons. As it is shown in figure 4, the measured gamma-ray emission along the galactic plane is higher with respect to the DRAGON models, That finding might be explained accounting for the contribution of unresolved sources and a contribution from mis-modeled known sources. For longitudes between 30° and 35°, corresponding to a region relatively less populated of supernova remnants and energetic sources, however we see a tendency for both the HAWC measurement and the gamma model fluxes to rise. This tendency will be studied further.

4. Conclusions

We presented the analysis of the spectrum and the angular distribution of the diffuse γ-ray emission measured by HAWC from the GP above 1 TeV. We determined both the longitude and latitude profiles of the emission and we tested our results against the predictions of the diffuse emission estimated by two reference models, the *base* and *gamma* models, based on the DRAGON code for particle transport in the Galactic Plane. While the two models well reproduce Fermi-LAT data at large Galactic longitudes, they have quite different behaviour in the innermost region of the GP. Above TeV energies our results show that the *gamma* model might provides a more satisfactory description of the HAWC data with respect to the (conventional) base model, however, HAWC results are significantly higher than both gamma and base models. This analysis will be improved after we use the results of point and extended source analyses undergoing within the HAWC collaboration.

Our result will be used to calibrate the DRAGON code at TeV energy range, which will help us to further refine our analysis in future. Additionally, we showed a comparison between the diffuse flux measured by HAWC and Milagro [5] for the inner and the outer part of Galaxy plane. In order to take into account the effect of unresolved sources on our estimate of the diffuse emission, a more significant accumulated data is needed.

Notes

[1] https://heasarc.gsfc.nasa.gov/docs/cgro/egret/

[2] https://fermi.gsfc.nasa.gov/

[3] Milagro was a ground-based water Cherenkov detector designed to detect very high energy γ-rays. it stopped taking data in April 2008 after seven years of operation.

[4] https://github.com/threeML/threeML

[5] http://tevcat.uchicago.edu/

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