HAWC Sensitivity to Diffuse Emission

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Abstract: Very high energy (VHE) diffuse gamma-ray emission measurements are an excellent probe of cosmic-ray acceleration, propagation, and density distribution at different locations within our Galaxy. Theoretical models of diffuse gamma-ray emission at GeV and TeV energies usually assume that the cosmic-ray flux and spectrum measured at Earth are representative of the typical flux and spectrum present throughout our Galaxy. But there has been some evidence that these models do not explain the large scale Galactic diffuse gamma-ray emission measured by several experiments at the highest energies. At TeV energies for example, the Milagro experiment reported a significant enhancement of diffuse emission with respect to models of the Cygnus region (measured emission = 8x predicted) and the inner Galaxy (5x). Observations by the HESS telescope of a molecular cloud near the center of the Galaxy also revealed an enhancement and a harder spectrum than expected if the cosmic ray flux were the same as the flux at Earth. In addition to improving theoretical modeling, measuring the diffuse and extended emission in our Galaxy with better sensitivity will help us better understand these enhancements, put tighter constraints on Galactic cosmic-ray emission, and distinguish between hadronic and leptonic acceleration and propagation models. The HAWC observatory, an all-sky high-altitude water Cherenkov detector array currently being constructed in Mexico, will be 15 times more sensitive than the Milagro detector and will be completed in Fall 2014. The simulated sensitivity of the array to Galactic diffuse gamma-ray emission under different model assumptions will be presented.

Keywords: cosmic rays, gamma rays, diffuse emission, simulation

1 Introduction

The origin and acceleration mechanisms that produce the cosmic rays that fill our Galaxy and are bombarding Earth from space have not yet been determined unambiguously. Favored candidate sources of Galactic cosmic rays (GRCs) are supernova remnants (SNRs) and pulsars. The standard production mechanisms for gamma-ray emission are interactions of cosmic rays (hadrons and electrons) with the matter and radiation fields in the Galaxy. Cosmic-ray hadrons interact with matter, producing neutral pions, which in turn decay into gamma rays, while cosmic-ray electrons produce TeV gamma rays by inverse Compton (IC) scattering off the interstellar radiation fields. At lower energies (MeV-GeV) bremsstrahlung from cosmic-ray electrons also contributes to gamma-ray emission.

The detection of TeV gamma rays and X-rays from the same locations within SNRs provides strong evidence that electrons are accelerated in SNRs [1]. However, no definite evidence for the acceleration of protons and nuclei in SNRs has been found and it is not clear whether the proton and electron accelerators are of a different nature. The direct observation of cosmic rays from the candidate injection sites such as SNRs and pulsars is not possible since cosmic rays escape acceleration sites and eventually propagate into the Galactic magnetic field where they are deflected and subsequently mix with the bulk of cosmic rays, also known as the cosmic-ray background or 'sea' of cosmic rays. By measuring diffuse TeV gamma-ray emission the density and spectra of both the cosmic-ray sea and young cosmic-ray accelerators throughout our Galaxy can be studied.

In general, the TeV sky appears to show more small scale structures than the sky at MeV-GeV energy (with the exception of the fairly recent discovery of the 'Fermi bubbles' [2]). Close to acceleration sites with ambient target material, gamma rays are produced and may contribute to the diffuse emission at TeV energies. This emission is unique in that it traces the transitional energy regime between 'sea' and freshly released cosmic rays. The detection of extended/diffuse gamma-ray emission near these sites at close to 100 TeV would be a sign of cosmic-ray acceleration up to 10^{15} eV in such objects. [3, 4, 5, 6]. In addition, it will be interesting to investigate if the Fermi bubble structure extends to TeV energies.

As a wide field of view instrument, the High Altitude Water Cherenkov (HAWC) observatory is well suited to address the open question of cosmic-ray origins through the measurement of diffuse and extended TeV gamma-ray emission from large-scale areas in our Galaxy. The telescope is capable of providing an unbiased survey of a large portion of the Northern Hemisphere down to regions close to the Galactic center at energies > 100 GeV (see Figure 1). The HAWC data will allow for the study of diffuse emission from large areas along the Galactic plane or from structures such as the Fermi bubbles.

2 Previous Measurements

In diffuse gamma-ray studies the measured spatial and spectral energy distributions of the emission are usually compared to model predictions based on the three dominant standard processes, neutral pion decays, IC scattering, and bremsstrahlung. Thus the relative contribution of hadronic and leptonic gamma-ray production mechanisms is investigated.

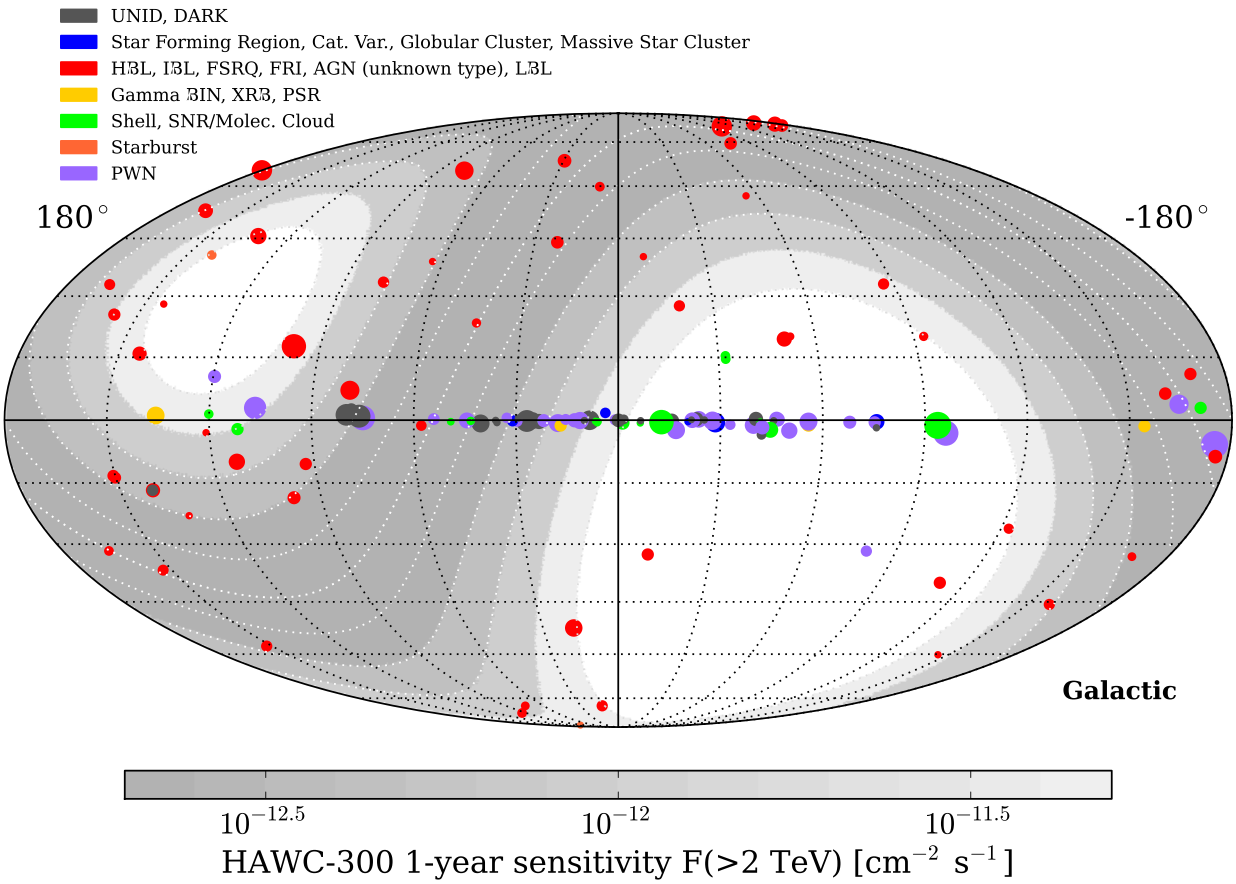

Fig. 1: The TeV sky visible to the HAWC observatory in Galactic coordinates. The detector sensitivity is declination dependent and darker grey bands indicate better sensitivity. Source classes of very-high gamma-ray emission as obtained with TeVCat[7] are overlaid.

The results of previous studies have been inconclusive. The H.E.S.S. telescope detected VHE diffuse emission from the Galactic center ridge, which is correlated with giant molecular clouds [8]. The spectrum of this emission is significantly harder than the spectrum of the diffuse emission predicted with the cosmic-ray spectrum measured at Earth. The resulting enhancement of the measurement with respect to the prediction amounts to a factor of 3-9. This enhancement, similarly visible for the Sgr B Region, implies that the high-energy cosmic-ray density is much higher than the local value (up to 10 times). In addition, the paper concludes that the cosmic rays producing the gamma rays are likely protons and nuclei rather than electrons because of the measured hardness of the gamma-ray spectrum [8].

The first measurement of diffuse gamma-ray emission above 3.5 TeV from a large region of the Galactic plane (40 < Galactic longitude < 100) performed by the Milagro experiment indicated the existence of a TeV excess [9]. In addition, the Milagro experiment measured the diffuse emission near 12 and 15 TeV from the Cygnus region of the Galaxy [10, 11] and also found an excess compared to predictions of GALPROP, a numerical model of cosmic-ray propagation in the Galaxy [12, 13, 14]. Studies of the latitudinal profiles of the diffuse emission were also performed by the Milagro collaboration. It was found that the measured shape does not agree well with the shape predicted by the GALPROP model that is optimized to explain the GeV gamma-ray excess previously measured by the EGRET experiment. A slight improvement was achieved by increasing the relative contribution from the pion decay channel. But even after this fit to the measured profiles the χ^2value still indicated a poor agreement between the GALPROP model and the Milagro data.

The recent results from Milagro and H.E.S.S. support the hypothesis that the cosmic-ray flux is likely to vary throughout the Galaxy. Both excesses have also been studied for an association with the dark matter particles [15, 16, 17, 18], but for the Milagro result the explanation that the excess is due to unresolved sources is more likely [19]. In contrast, recent measurements with the Fermi space telescope show no such discrepancy between the conventional assumption of the locally measured cosmic-ray spectrum and measurements of propagated high energy gamma rays [20, 21]. If the Milagro observations are compared with the conventional GALPROP assumption (see Figure 3) significant excesses are seen both in the Cygnus region (65^o < gal. longitude < 85^o, 8x) and in a region outside of Cygnus closer to the Galactic Center (30^o < gal. longitude < 65^o, 4.7x) [22].

3 Expected HAWC Performance

The Milagro data are not sensitive enough for a spectral energy distribution measurement, so interpretations for the diffuse excess range from leptonic processes - though

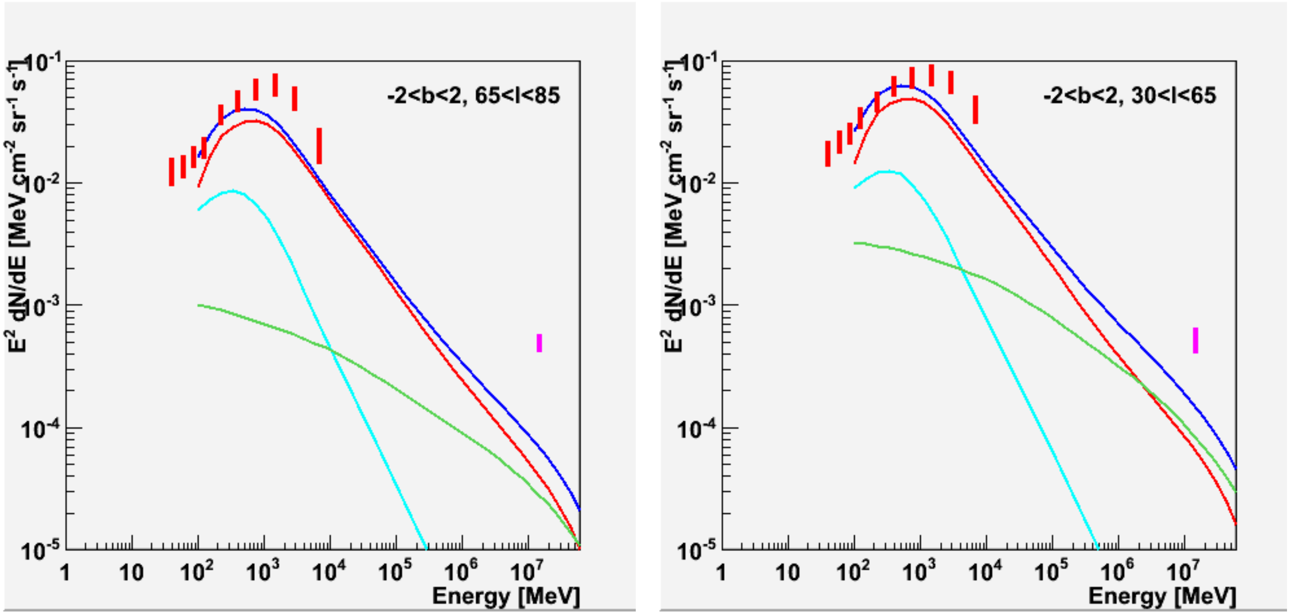

Fig. 2: Measured diffuse differential gamma-ray fluxes (EGRET in red, and Milagro in magenta) compared with GALPROP predictions [10, 12, 13, 14]. IC (green), pion (red), and bremsstrahlung (teal) contributions and the total predicted flux (blue) are shown for the Cygnus region and the inner Galaxy.

disfavored by the expected fast cooling of highly energetic electrons - to freshly accelerated cosmic rays that are injected into the interstellar medium. The latter explanation seems simpler in Cygnus, a region that hosts intense star formation activity and is abundant with molecular clouds and candidate cosmic-ray sources. Based on [23] it is estimated that more than ten strong young accelerators in the Cygnus region are needed to explain the excess emission, but in order to definitely answer the question if the gamma-ray production is of hadronic or leptonic nature a spectral measurement is necessary. The differential sensitivity of the HAWC observatory is expected to be good enough to perform such a measurement. In addition, due to its improved point source sensitivity (15x that of the Milagro detector) and angular resolution ($<$ 0.2 deg for energies $>$ 10 TeV), the experiment is expected to detect more point and extended sources with greater accuracy. These will be subtracted from the total flux along the Galactic plane to constrain the truly diffuse emission better. HAWC will also provide an opportunity to perform morphological studies that will reveal the location of cosmic-ray production and acceleration. This will be of particular interest in the Cygnus region that has been the subject of numerous studies recently. None of these studies reach the very high gamma-ray energies that can be measured with the HAWC observatory (up to $\sim$100 TeV). Moreover, HAWC will have access to the Galactic Center ridge, a region where the H.E.S.S. experiment has detected gamma-ray signatures that are inconsistent with expectations based on the locally measured cosmic-ray spectra [8].

4 Outlook

We will present the sensitivity of HAWC to and significance maps of diffuse gamma-ray emission expected after one to five years of operation of the complete array. We will test the detector response to alternative models of diffuse emission such as GALGROP, and a model based on the Milagro result [10, 12, 13, 14]. Figure 3 shows a first simulated map of the number of events that are due to galactic diffuse gamma-ray emission as predicted by GALPROP after one year of HAWC operation. A detailed description of the software package that is used to simulate the detector behavior can be found elsewhere in these proceedings [24].

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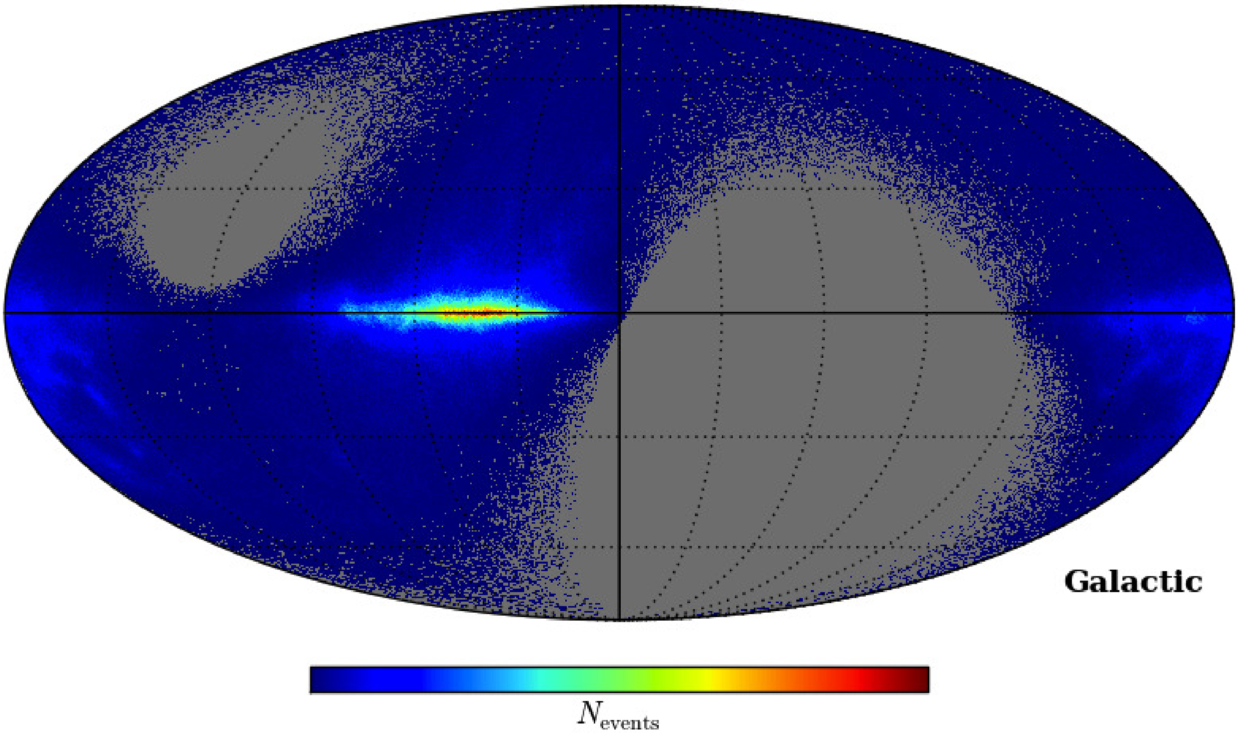

Fig. 3: Galactic map of one year of diffuse gamma rays observed with the completed HAWC detector.

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