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UNDERSTANDING THE VERY HIGH ENERGY γ -RAY EMISSION FROM A FAST SPINNING NEUTRON STAR ENVIRONMENT

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UNDERSTANDING THE VERY HIGH ENERGY γ -RAY EMISSION FROM A
FAST SPINNING NEUTRON STAR ENVIRONMENT

By

Chad Allen Brisbois

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Physics

MICHIGAN TECHNOLOGICAL UNIVERSITY

2019

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This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Physics.

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Nomenclature

This section provides a useful list of commonly used abbreviations and acronyms used in this document.

HAWC	High Altitude Water Cherenkov
PMT	PhotoMultiplier Tube
WCD	Water Cherenkov Detector
TS	Test Statistic
PWN	Pulsar Wind Nebula
VHE	Very High Energy
electrons	electrons and positrons
leptons	electrons and positrons
CMB	Cosmic Microwave Background
NIR	Near InfraRed
SNR	SuperNova Remnant

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lost things in this pursuit. In one way or another, I lost Amy, my grandfather, and my ability to eat hummus. I hope the next six years I spend after grad school I grow as much as I did in my time here. I started graduate school with a lot of optimism about the world, and this has morphed into something...different. I am still optimistic, but much like the study of physics, reality has proven to be stubbornly resistant to simple models of personal philosophy. Therefore, I must express my love and gratitude for those who spent time at Michigan Tech with me: Hugo Ayala-Solares, Teresa Wilson, Kiley Spirito, Scott Rutterbush, Kevin Waters, Joseph Niehaus, Zoë Coombs, Lindsay & Tyler Capek, and Lisa Egghart. All of you have helped me overcome so much, and I could not have made it without you.

To intentionally misquote Benjamin Sisko in the final episode of Star Trek: Deep Space 9, *No matter what the future holds, no matter how far we travel, a part of us, a very important part, will always remain here, in Houghton at Michigan Tech.*

Abstract

Pulsars, and their associated pulsar wind nebulae, are factories producing high energy electrons and positrons in our galaxy. The Dragonfly nebula is a Vela-like pulsar wind nebula in the Cygnus region powered by the spin down of PSR J2021+3651. The TeV γ -ray source 2HWC J2019+367 was originally discovered in 2007 by the Milagro Observatory and has been associated with this pulsar. This dissertation presents the first detailed morphological and spectral study of the TeV emission up to the highest photon energies of 2HWC J2019+367. This analysis has identified two sources, the extended source HAWC J2019+368 and the point source HAWC J2016+371. The spectral energy distribution for HAWC J2016+371 is fit by a power law with a flux normalization at 10 TeV of $2.6 \pm 0.7 \times 10^{-15} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ and a spectral index of $\alpha = -2.32 \pm 0.18$. This represents the first independent confirmation of emission from supernova remnant CTB 87 at TeV energies. The γ -ray spectral energy distribution of HAWC J2019+368 significantly prefers a log parabola function, rather than a pure power law. The flux normalization at 10 TeV is $4.05 \pm 0.26 \times 10^{-14} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ cm}^{-2}$, with a spectral index $\alpha = -2.02 \pm 0.06$ and curvature parameter $\beta = 0.29 \pm 0.05$. The morphology of HAWC J2019+368 is an asymmetric gaussian with semi-major axis $a = 0.368^\circ \pm 0.021^\circ$ and eccentricity $e = 0.941 \pm 0.017$. The γ -ray flux measured in this analysis directly corresponds to the measurement of electrons with energies up to $\sim 200 \text{ TeV}$. An electron spectrum is fit to the data for HAWC J2019+368, assuming

that the production of γ -rays is due to inverse Compton emission, and shown to be well within the energy budget of PSR J2021+3651. This supports the interpretation of the emission of HAWC J2019+368 being almost entirely due to the electrons and positrons produced by PSR J2021+3651.

Introduction: The High Energy Universe & the Role of Fast Spinning Neutron Stars

The high-energy universe is a very general term to describe the environments in which the most extreme processes in nature can occur. The limits of particle acceleration in the universe are beyond the reach of terrestrial particle accelerators by several orders of magnitude [1, 2]. Traditionally, the sources of high energy particles in our galaxy has been hypothesized to be SuperNova Remnants (SNRs). This is due to the immense amount of energy put out by a supernova, which is up to $\sim 10^{53}$ erg [3]. In comparison, the amount of energy released by the sun per second is 10^{33} erg [3], meaning that a supernova releases the energy equivalent to approximately a trillion years of solar output. This provides sufficient energy to accelerate particles such as protons and electrons to the highest energies possible. Importantly, the γ -rays

that result from these accelerators do not originate from blackbody (i.e. thermal) radiation, but rather from non-thermal processes due to the fundamental interactions of the elementary particles themselves.

Pulsars are formed as the remaining husk of the core of a star that has produced a SuperNova (SN). They are fast spinning neutrons stars that produce light over a wide energy range, from Radio to TeV energies either continuously or periodically [4]. They produce electron positron pairs in a process known as a polar cap cascade [4, 5] which enables production of γ -rays via inverse Compton scattering. This leads to the development of a wind of electrons and positrons, forming structures called Pulsar Wind Nebulae (PWNe). PWNe feature a variety of morphological features depending on the environment they are embedded in, and the initial conditions of the pulsar they are produced by. Pulsars with high velocities may form so called “bow-shock” PWN due to the SN giving birth to them providing a large initial kick velocity resulting in the pulsar traveling supersonically through the interstellar medium [4]. One major tool of understanding PWNe and pulsars is in studying the synchrotron radiation in X-rays produced by PWNe and pulsars. More recently, very extended regions of TeV γ -ray emission has been discovered by HAWC around the Geminga and Monogem pulsars [6]. These represent the first two of a new source class, which has been named TeV Halos [7]. Because PWNe and TeV Halos derive their energy from the spindown of their associated pulsar, and together are referred to here as “Pulsar powered systems”.

There are two primary techniques to detecting Very High Energy (VHE) γ -rays. Both methods are discussed in detail in Chapter 1. They rely on the development of an extensive air shower in the atmosphere after a γ -ray interacts near the top of the atmosphere, which triggers a cascading series of interactions producing lower energy γ -rays along with electrons and positrons [8]. Air Cherenkov telescopes observe the Cherenkov light of the high energy charged particles traveling through the air. Air shower arrays sample the footprint of the air shower as it reaches the ground [8]. They are complementary techniques, with air Cherenkov telescopes offering excellent point source sensitivity and angular resolution, while air shower arrays can observe large portions of the sky at once and offer better sensitivity to the highest photon energies due to their high uptime [8].

It is currently unknown what the highest energy particles are accelerated to in pulsar power powered systems, but recent models [5] show that it is likely that electrons and positrons in excess of 30 TeV are produced directly in the magnetosphere of pulsars. Whether they undergo further acceleration in the PWN or not is something which requires further study. HAWC and other instruments sensitive to VHE γ -rays are able to directly measure the highest energy electrons because the interactions between photons and electrons at those energies follows a relationship which is independent of assumptions about the magnetic field [9, 10]. Answering the question, “What is the highest energy electron that can reasonably be expected to result from the TeV emission produced by the system powered by PSR J2021+3651?”, is the primary

scientific question answered in this thesis. To do this, it is required that a detailed spectral and morphological study is done of this region to understand the emission seen by HAWC. Previously, the region was described by a 0.7° disk [11] and designated 2HWC J2019+267.

This thesis is organized as follows. The first chapter is an introduction and review of the field at large, including basic principles, sources of particle acceleration in our galaxy, and detection methods used to observe γ -rays. The second chapter provides a description of the HAWC Observatory, and contains reconstruction details that are relevant to the analysis and results presented in this dissertation. The statistics chapter (Chapter 3) reviews vital statistical methods and describes the methods used for determination of model selection and fitting. In Chapter 4, a detailed description of Pulsar powered systems is given, including the theoretical background necessary to understand the particle spectra and transport distinguishing these systems. A review of the detection of multi-wavelength emission from the region of 2HWC J2019+367 [11] is provided in Chapter 5, followed in Chapter 6 by a detailed description of the HAWC data analysis I performed. In the final chapter, I present my scientific results and main conclusions.

Chapter 1

VHE γ -ray Emission in Space and Ground Based Detection

The study of Very High Energy (VHE) γ -rays is a significant challenge, with the first detection of a source occurring in 1989 [12]. The term VHE has historically referred to the energy range 30 GeV to 30 TeV [13]. That definition is slowly changing [8]. Today the terms VHE and TeV (referring to γ -rays in the TeV energy range, possibly in excess of 30 TeV) are used more interchangeably. The primary mechanisms which produce photons at these energies are non-thermal, meaning that the emission results not from blackbody radiation, but rather from fundamental interactions among the particles themselves. The methods to detect these photons are also dramatically different from the traditional ways of looking into space, rather than using lenses

and mirrors to bend and focus the many photons emitted, it is necessary to measure a shower of particles in the atmosphere cascading toward the Earth initiated by individual photons.

1.1 Non-thermal Radiation

The known mechanisms giving rise to non-thermal radiation in the universe are Bremsstrahlung, Synchrotron radiation, Inverse Compton scattering, and Pion (π^0) Decay. These each involve interactions between leptons (electrons and positrons) and hadrons (primarily protons). Note: Throughout this document, c refers to the speed of light.

1.1.1 Bremsstrahlung

Bremsstrahlung, or braking radiation, is the process by which charged particles emit photons during deceleration. The most important example of this is in the context of a high-energy electron interacting with an atomic nucleus [14]. The energy loss rate is proportional to Γ^{-3} at high energies, ($\Gamma = (1 - (v/c)^2)^{-1/2}$), where v is the velocity of the electron), and is expected to be subdominant at TeV energies [13]. For protons, bremsstrahlung is responsible for a majority of the production of γ -rays

below ~ 1 GeV [3].

1.1.2 Pion Decay

Neutral Pions are one possible result of collisions between atomic nuclei. During these collisions (also called spallation events), nuclei are fractured and the resulting non-nuclei products are charged and neutral pions [14]. Neutral pions decay to produce γ -rays (after $\sim 10^{-16}$ s), and are responsible for a majority of γ -ray production above 1 GeV [3]. Charged pions decay to muons and neutrinos ($\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$) and are an important process for neutrino detection experiments such as IceCube [3]. Pion decay is generically referred to as a hadronic process because the production of pions (neutral or otherwise) involves nuclear interactions between hadrons.

1.1.3 Synchrotron Radiation

Synchrotron (also referred to as magneto-Bremsstrahlung) radiation is the process by which electrons emit radiation as a result of being (de)accelerated in a circle due to a magnetic field [14]. Following basic electromagnetism, the frequency, ν_g , of rotation along the gyroradius of an electron of mass m_e moving at speed v in a magnetic field B is

$$\nu_g = \frac{eB}{2\pi m_e} \quad (1.1)$$

and in the relativistic regime, Equation 1.1 becomes

$$\nu = \Gamma^2 \nu_g \quad (1.2)$$

where

$$\Gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (1.3)$$

Assuming a power-law distribution of electrons with energies E and power law index p of the form $N(E) \propto E^{-p}$, and keeping in mind that the energy carried by the synchrotron photons are due to the energy loss of the electrons, it can be shown that the synchrotron spectrum, given by $J(\nu)$, the energy dependent emissivity per unit volume [14] is

$$J(\nu) \propto B^{(p+1)/2} \nu^{-(p-1)/2} \quad (1.4)$$

This useful relationship (Equation 1.4) allows us to probe the electron spectrum by making appropriate assumptions about the magnetic field strength. Synchrotron emission is important in the study of PWN, especially at X-ray energies [13, 14]. A useful relationship is described in [9] between the characteristic energy of an electron, E_e , and a synchrotron photon as,

$$E_e \approx 132 \left(\frac{E_X}{1 \text{ keV}} \right)^{0.5} \left(\frac{B}{3 \mu\text{G}} \right)^{-0.5} \text{ TeV} \quad (1.5)$$

Where E_X is the energy of a photon in X-ray, and B is the local magnetic field where the synchrotron radiation is being produced. Note this requires assumptions or additional information about the magnetic field to be available to estimate the energy.

1.1.4 Inverse Compton Scattering

Inverse Compton (IC) is the most important mechanism for electron energy loss at the highest energies. The energy loss rate for electrons at energies satisfying $\Gamma \hbar \omega \ll m_e c^2$ is remarkably similar to that for synchrotron radiation,

$$\left(\frac{dE}{dt}\right)_{IC} = \frac{4}{3}\sigma_T c u_{rad} \beta^2 \Gamma^2 \quad (1.6)$$

$$\left(\frac{dE}{dt}\right)_{sync} = \frac{4}{3}\sigma_T c u_B \beta^2 \Gamma^2 \quad (1.7)$$

where σ_T is the Thomson cross-section, u_X is the radiation ($X = rad$) density or magnetic ($X = B$) field density, and β is the electron speed as a fraction of the speed of light. When the above limit is no longer satisfied, the full Klein-Nishina cross section must be used rather than σ_T , and the energy loss rate is much less cleanly written down. A detailed analysis can be found in [15]. This occurs above a few TeV if only the CMB/IR photon fields are considered [10]. IC scattering is the primary form of energy loss for electron and positrons at energies relevant to HAWC [15]. The typical energy for an electron scattering of the CMB is given in [9] as,

$$E_e \approx 17.2 \left(\frac{E_\gamma}{1\text{TeV}}\right)^{0.5} \text{TeV} \quad (1.8)$$

Where E_e and E_γ is the electron and γ -ray energies, respectively. This allows for the direct measurement of electron energies independent of information about the magnetic field.

1.2 Probing Astrophysical Particle Accelerators with γ -rays

The universe contains many diverse sites for particle acceleration, including shell-type SNRs, Pulsars, PWNe, Binary systems, Active Galactic Nuclei (AGN), and colliding neutron stars [10, 16–18]. Charged particles are deflected in Galactic and Extragalactic magnetic fields, which makes it difficult to trace them back to their source. This fact motivates the development of detection techniques for γ -rays, which are produced in the interactions of charged particles in or near their acceleration sites via processes described in the previous section. The γ -rays are not deflected on their way to Earth, because they carry no charge.

The source in question dictates the precise conditions for particle acceleration and subsequent detection at Earth. For γ -rays accelerated in the jets of AGN, the interactions between high and low energy photons cause TeV photons to lose energy into the extragalactic background light (EBL). This EBL absorption is an additional effect on top of the redshift that affects all photons traveling from cosmological distances [10]. Pulsars directly accelerate particles in their rotating magnetic fields [4, 16] and produce radiation primarily via inverse Compton and synchrotron radiation. Any object which generates shocks (such as shell-type SNRs or PWN) may also produce

high energy particles by diffusive shock acceleration [14, 18].

1.3 Detection Techniques

The detection techniques for TeV γ -rays rely on the Earth’s atmosphere to interact with the primary particle to produce what is known as an Extensive Air Shower (EAS). There are two types of detectors to measure EASs: Imaging Air Cherenkov Telescopes (IACTs) and EAS arrays [8]. IACTs measure the EAS as it develops in the atmosphere by detecting the Cherenkov light emitted by the charged particles in the EAS. EAS arrays directly sample the air shower particles as they reach the surface of the Earth (sometimes referred to as the shower “footprint”). HAWC is an EAS array composed of an array of Water Cherenkov Detectors (WCDs). Both IACTs and WCD depend on detecting Cherenkov light to observe the shower, to observe the development of the shower as it travels through the atmosphere or to detect the arrival of particles at the ground, respectively.

1.3.1 Cherenkov Light

Cherenkov light is the radiation emitted when charged particles travel through a medium faster than the speed of light in that medium [19]. As shown in Figure 1.1,

the Cherenkov angle θ_C in a material with refractive index n is given by,

$$\begin{aligned} \cos(\theta_C) &= \frac{\frac{c}{n}t}{\beta ct} = \frac{c/n}{v} \\ &= \frac{1}{\beta n} \end{aligned} \tag{1.9}$$

This is useful because in many cases $\beta = v/c$ can be assumed to be 1 because only relativistic particles are able to penetrate the atmosphere, therefore the Cherenkov angle is relatively fixed for a particular material. For water ($n = 1.330$ [20]), the Cherenkov angle is 41.3° . For air ($n = 1.000293$ [20]), the Cherenkov angle is 1.387° . This governs the design of IACTs and WCDs

1.3.2 EAS Arrays

EAS arrays such as HAWC work via sampling the particles in an extensive air shower [8, 21]. When the charged particles traveling in the air shower reach the HAWC WCDs, they enter the water in the tanks. The subsequent emission of Cherenkov light is detected by the four upward-facing PhotoMultiplier Tubes (PMTs) at the bottom of the water inside the HAWC WCDs. Because the Cherenkov light is sampled within a light-tight black PVC bladder, this enables ground arrays to operate during the day, allowing for nearly 100% uptime. The timing and number of photo-electrons (PEs) liberated by the cherenkov light for each PMT enables reconstruction of the

Figure 1.1: Diagram of Cherenkov light geometry. $\beta = v/c$

parameters of the air shower, such as the direction and energy. To determine if the air shower was initiated by a γ -ray or a hadron, the footprint of the shower on the array is examined [21]. More detail about shower reconstruction with the HAWC Observatory will be discussed in Chapter 2.

1.3.3 Imaging Air Cherenkov Telescopes

Imaging Air Cherenkov Telescopes operate by directly observing the Cherenkov light of the air shower propagating through the atmosphere. When the air Cherenkov

technique was first being pioneered, the shower reconstruction was based on simple fitting of the image parameters (known as the Hillas Parameters [22]) which described the shape of the Cherenkov light on the ground by an ellipse with fit parameters corresponding to length, width, and rotation of the ellipse. As time went on, likelihood methods were developed to enable more precise phenomenological parameterizations of the appearance of the image of ellipse in the cameras[23]. More recently, direct simulations of air showers have enabled air shower templates to be constructed as functions of shower energy and zenith angle, which characterize the appearance of the air shower in the IACT directly [24].

Chapter 2

The High-Altitude Water Cherenkov Observatory

The High Altitude Water Cherenkov (HAWC) Observatory is located at $18^{\circ}59'41''\text{N}$, $97^{\circ}17'30.6''\text{W}$ on Sierra Negra in Mexico [11]. It is a γ -ray observatory most sensitive to photon energies above 1 TeV [11, 21]. Although sensitive to both cosmic-rays and γ -rays, the analysis presented here uses only γ -ray data. HAWC consists of 300 Water Cherenkov Detectors, each of which contain 4 PMTs (See Figure 2.1). Each WCD is 7.3 m diameter and 5 m tall, containing approximately $2 \cdot 10^5$ L of water. A diagram of HAWC can be seen in Figure 2.2. The gap in tanks near the middle of the array is the location of the counting house, where the data is collected and written to hard disks.

Figure 2.1: This is a schematic of one of the WCDs used in HAWC. There are three 8" Hamamatsu R5912 PMTs with a 10" Hamamatsu R7081 PMT in the center [11, 21]. The blue traces are light paths taken by Cherenkov light emitted by a charged particle entering the tank. Image from [21].

Figure 2.2: Diagram of HAWC, with PMT and WCD locations given.
Figure from [11].

The HAWC Observatory uses the timing and brightness of the Cherenkov light detected by the WCDs to reconstruct the direction and energy of each extensive air shower incident upon the WCD array (more details about reconstruction beyond those contained in this chapter can be found in [21]). Although most air showers are not caused by γ -rays, the background rejection methods used by HAWC allow

us to identify γ -ray showers with high purity [11, 21]. Simulated events are shown in Figures 2.3 and 2.4 to illustrate the two types of events observed by HAWC. Figure 2.3 shows a simulated γ -ray shower in the detector by timing and the measured charge in the PMTs. In Figures 2.3 and 2.4, the red star and line indicates the core of the shower (discussed in Section 2.1) and the direction the air shower came from. The direction of the air shower is given in the title in Right Ascension (RA) and Declination (Dec). The compactness value (discussed in Section 2.3.1) is given labeled as CXPE40. The PMT measuring the largest charge beyond 40 m from the core (indicated by the dashed circle), is labeled with a red circle. Looking at the timing distribution, the size indicates the charge measured in that PMT as verified by looking at the charge distribution.

Figure 2.3: A simulated γ -ray event on the HAWC array, showing the footprint on the array measured in time and measured charge Q in each PMT. The simulated γ -ray had an energy of 15 TeV. The values in Run, TS, and Ev are diagnostic values referring to the number of simulated showers in the ensemble, of which this is one example.

Figure 2.4: A simulated proton event on the HAWC array, showing the footprint on the array measured in time and measured charge Q in each PMT. The simulated proton had an energy of 8 TeV. The values in Run, TS, and Ev are diagnostic values referring to the number of simulated showers in the ensemble, of which this is one example.

It is obvious by comparing Figures 2.3 and 2.4 that a hadron shower is clumpier by eye. Algorithmic expressions of this apparent qualitative feature is the basis for separating γ -ray showers from hadronic showers. This is one of the premises which makes HAWC the most sensitive of any instrument to γ -rays above 10 TeV (See Figure 16 in [11]). In the following I will discuss the main steps of the air shower event reconstruction of HAWC.

2.1 Core Reconstruction

The shower core is defined as the location where the main axis of the shower (which points in the direction of the original γ -ray or cosmic-ray) passes through the plane

defined by the HAWC WCD array (see Figures 2.6 and 2.3). Locating this point on the detector is critical for accurate reconstruction of the extensive air shower. The method used in HAWC is referred to as the Super Fast Core Fit [21], which defines the charge, S , in the i th PMT at location $\vec{x}_i$ as, S_i , around the core location $\vec{x}_c$ as

$$\begin{aligned}
S_i &= S(A, \vec{x}_i, \vec{x}_c) \\
&= A \left(\frac{e^{\left(-\frac{|\vec{x}_i - \vec{x}_c|^2}{2\sigma^2}\right)}}{2\pi\sigma^2} + N \left(0.5 + \frac{|\vec{x}_i - \vec{x}_c|}{R_m} \right)^{-3} \right)
\end{aligned} \tag{2.1}$$

The parameters fit are the location of the core (represented by $\vec{x}_c$) and the amplitude A . The remaining values (σ and $R_m \approx 120$ m) are fixed to precomputed values from simulation giving the width of the Gaussian, σ , and the Moliere radius, R_m , (see Section 2.4 from [21]). The distance to the shower core, $r_i = |\vec{x}_i - \vec{x}_c|$, is discussed further in Section 2.2.1.1. The fit function given in Equation 2.1 is meant to approximate an NKG function [3] as a Gaussian with a thick tail which mimics the behavior of the NKG function far from the core of the shower. The NKG function is so named for the first people to derive it: Nishimura, Kamata, and Greisen [3]. It describes the number density of particles in the air shower, known as the lateral distribution function (LDF). It only accounts for showers which interact electromagnetically, making it ideal for γ -ray initiated showers. Events initiated by protons (and other nuclei) interact in the atmosphere in ways that are not electromagnetic in nature, and so must

be described by modified NKG functions to accommodate these additional strong or weak interactions [3]. The result of two fits to air showers is shown in Figure 2.7 for a cosmic-ray (hadron) and for a γ -ray shower are shown. There you can also see that a γ -ray has a smoother profile, this is referred to LDF [3, 25]. The LDF of a shower contains information about the energy of the shower [3, 25, 26] and is the basis for energy estimation techniques on HAWC [27].

2.2 Angular Reconstruction

The goal of angular reconstruction is to determine the zenith and azimuthal directions θ, ϕ that a shower originated from. The method described here is largely based on Appendix B from [28], although the notations have been updated. Angle reconstruction is accomplished by the least squares method, usually expressed as the model (and parameters) that minimize χ^2 by

$$\chi^2 = \sum_{i=1}^N f_i^2 \quad (2.2)$$

The residual f_i represents the difference between the model and the data for the i th PMT triggered (colloquially referred to as a PMT “hit”), of which there are N in a particular shower. It is a function of the position of a PMT, the charge recorded by

the PMT, and distance from the core For angle reconstruction, we generally assume that the shower front can be well approximated by a plane arriving onto the detector.

Each PMT hit is assigned a weight according to the charge measured by the PMT. PMTs located nearer the core of the shower will record a larger charge than those further away, and therefore will matter more to the fit than those further away, which are also more likely to be noise hits rather than being from the air shower.

2.2.1 Basic Plane Fit

The simplest way to parameterize the incident direction of an EAS is to use a plane to describe the front of shower particles that sweeps across the array. Using the previously determined core position, we can minimize the square of the residuals in Equation 2.2 as, to figure out the direction the shower came from. One substitution is performed to translate the shower direction, θ, ϕ , into a normal coordinate vector so that the shower front plane can be defined as a dot product. This is expressed by

$$\hat{n} = \begin{pmatrix} u \\ v \\ w \\ c \end{pmatrix} = \begin{pmatrix} \sin(\theta)\cos(\phi) \\ \sin(\theta)\sin(\phi) \\ \cos(\theta) \\ c \end{pmatrix} \quad (2.3)$$

The model of the plane then also includes PMT positions (x_i, y_i, z_i) and the arrival time t_i for each PMT, and therefore is a 4-dimensional vector, using the speed of light, c , to convert units to lengths. This is given by,

$$\hat{n} \cdot (\vec{x}_i - \vec{x}_c) = \begin{pmatrix} u \\ v \\ w \\ c \end{pmatrix} \cdot \left[\begin{pmatrix} x_i \\ y_i \\ z_i \\ t_i \end{pmatrix} - \begin{pmatrix} x_c \\ y_c \\ z_c \\ t_0 \end{pmatrix} \right] \quad (2.4)$$

This represents a model which the shower is fit to fitting u , v , w , and t_0 . This is subject to the additional constraint that $u^2 + v^2 + w^2 = 1$, which comes from the definition of u , v , w , in Equation 2.3. We can then write our weighted residual f_i as Equation 2.5, by weighting by the charge (σ_i) recorded by the PMT as,

$$f_i = \frac{(ct_i - ct_o + u(x_i - x_c) + v(y_i - y_c) + w(z_i - z_c))}{\sigma_i} \quad (2.5)$$

Due to the lack of constraint on t_0 , it is possible to take the derivative of Equation 2.2 with respect to ct_0 , set it to zero, and solve for ct_0 . This optimal ct_0 is,

$$ct_0 = \frac{\sum_{i=1}^N \sigma_i^{-2} [ct_i + u(x_i - x_c) + v(y_i - y_c) + w(z_i - z_c)]}{\sum_{i=1}^N \sigma_i^{-2}} \quad (2.6)$$

The remaining parameters must be iterated upon using numerical techniques to determine the optimal values for θ and ϕ .

In the present HAWC reconstruction algorithm, the radius is calculated in the ground coordinate system. This is generally an acceptable approximation because the distance of a PMT from the core for a shower from directly overhead is minimal.

2.2.1.1 Ground Coordinates

In ground coordinates, the distance $r_i = |\vec{x}_i - \vec{x}_c|$ (See Section 2.1 for an example application) from a shower core is calculated simply as

Figure 2.5: Shower Curvature Diagram, Note: θ is the zenith angle of the shower.

Taken from Figure 9.1 from [25]

$$r_i = \sqrt{(x'_i - x_c)^2 + (y'_i - y_c)^2 + (z'_i - z_c)^2} \quad (2.7)$$

with the m_c being the core position, and m'_i being the position of the i th PMT in the generic HAWC coordinate system. This is analagous to the distance between the shower detectors measured along the page in Figure 2.5. This is currently how distance from the core is calculated for algorithms such as core reconstruction.

2.2.1.2 Shower Coordinates

For a vector denoting the position of the core $\vec{C}$, a vector denoting the position of a PMT $\vec{p}_i$, and the direction of a shower $\hat{n}$, the distance to the shower axis is given by,

$$r_i = \left\| \left(\vec{C} - \vec{p}_i \right) - \left[\left(\vec{C} - \vec{p}_i \right) \cdot \hat{n} \right] \hat{n} \right\| \quad (2.8)$$

It is easy to see that as the dot product approaches zero (the closer a shower is to zenith) these two methods are the same. This corresponds to r_1 in 2.5. A diagram I drew to demonstrate this is given in Figure 2.6, with r_1 given by the vector described in Equation 2.8.

2.3 Background Suppression

The main background in HAWC data is the nearly overwhelming contributions from hadronic air showers [21]. Extensive air showers produced by a γ -ray and a hadron are significantly different, as seen in Figures 2.3 and 2.4. A γ -ray interacts fundamentally electromagnetically, therefore the shower consists primarily of photons, electrons, and positrons. A hadronic extensive air shower consists of a wider variety of particles,

Figure 2.6: Diagram illustrating the distance from a PMT hit to the shower axis. Image Credit: *HAWC Picture of the Day: HAWC outriggers - October, 2017*

including muons, pions, secondary nuclei, as well as photons, electrons, and positrons [21]. Above ~ 30 GeV, muons outnumber hadronic particles in hadronic initiated air showers by nearly an order of magnitude (See Figure 15 from [8]). This leads to large, isolated hits in the detector that are useful for calibration. The (more numerous) secondary γ -rays or electrons/positrons produced in hadronic showers can initiate secondary electronmagnetic showers with some transverse momentum, which provides the origin of a feature that is referred to as “clumpiness”. HAWC uses two different techniques to identify and reject the inclusion of these events in our analysis;

“compactness” ($\mathcal{C}$) and “PINCness” ($\mathcal{P}$). To compare γ /hadron separation variables, $\sim 3 \cdot 10^6$ data events were taken, and a cut requiring $> 6.7\%$ of the array to be triggered in the event was performed, leaving $7.5 \cdot 10^5$ events. This restricts data used to only those used for data analysis (See Table 2.1). The data is compared to $1.7 \cdot 10^4$ simulated γ -ray initiated showers, so that it is clear that the data is substantially contaminated with non- γ -ray events. Common estimates are that somewhere between 1 in $10^3 - 10^4$ air showers seen by HAWC are due to γ -rays.

2.3.1 Compactness

Compactness, $\mathcal{C}$, is a relatively simple γ /hadron separation variable first developed for Milagro [29]. It is meant to identify muons in showers. Muons are seen as high PE, isolated hits which are far from the shower core, this is the “clumpiness” that is seen in Figure 2.3. It is a simple, but powerful variable defined by

$$\mathcal{C} = \frac{N_{\text{hit}}}{\text{CxPE}_{40}} \quad (2.9)$$

The parameter CxPE_{40} is defined as the largest charge measured by a PMT more than 40 meters from the reconstructed core location and N_{hit} is the number of PMTs triggered by the air shower event. Because hadronic air showers contain muons and

(a) γ -ray initiated air shower

(b) hadron initiated air shower

Figure 2.7: A comparison of the charge vs distance from the shower core for a hadronic shower and a γ -ray. The profile from the SFCF is shown, as well as the moving average of the PINCness parameter in 5 m wide annuli. These are taken from Figure 4 in [21].

sub-showers, the particles reaching the water tanks deposit energy in a less symmetric pattern about the shower axis than electromagnetic air showers. This can be seen in figure 2.7. The electromagnetic shower has fewer upward fluctuations in charge (Q_{eff}) than the hadronic shower. This property is also referred to as “clumpiness” in [21]. Larger values of $\mathcal{C}$ are indicative of an air shower which looks more like it was initiated by a γ -ray.

Figure 2.8: Distribution of Compactness values, comparing $\sim 7.5 \cdot 10^5$ data events with $\sim 1.7 \cdot 10^4$ simulated γ -ray showers.

You can see the distribution of compactness, $\mathcal{C}$, in Figure 2.8. Showers initiated by γ -rays are generally more compact until around $\mathcal{C} > 60$, beyond which the distributions appear to be similar.

2.3.2 The Parameter for Identifying Nuclear Cosmic-rays

The Parameter for Identifying Nuclear Cosmic-rays (PINCness), is a method of quantifying how smoothly the measured charge decreases as particles arrive further away

from the shower core. It is defined similarly to a χ^2 value:

$$\zeta = \log_{10}(Q) \quad (2.10)$$

$$\mathcal{P} = \frac{1}{N} \sum_{i=0}^N \frac{(\zeta_i - \bar{\zeta})^2}{\sigma_{\zeta_i}^2} \quad (2.11)$$

The charge (Q) is measured in annuli around the PMT, and the parameter $\mathcal{P}$ is computed in each annulus before being summed to produce the PINCness value. The weights σ_{ζ} are determined from simulated γ -ray air showers. Large deviations from the mean in each annulus increase $\mathcal{P}$ for showers which have a less smooth LDF. This is shown in Figure 2.7, a γ -ray shower has fewer features in its average annuli charge distribution (Note: $\langle \zeta \rangle = \bar{\zeta}$) measured than a hadronic shower. The PINCness distribution is shown in Figure 2.9.

As shown in Figure 2.9, smaller PINCness gives a larger fraction of photons than data for $\mathcal{P} < \sim 1.5$. The abrupt peak at 0 in data is primarily due to very small showers, which can have very small values for $\mathcal{P}$ due to the small number of hits in the event. The cuts applied for PINC can be as loose as ~ 3 [21], which keeps a substantial fraction of non- γ -ray events as well as keeping many of the γ -rays.

Figure 2.9: Distribution of PINC, comparing $\sim 7.5 \cdot 10^5$ data events with $\sim 1.7 \cdot 10^4$ simulated γ -ray showers.

2.4 Energy Estimation

Energy Estimation is critical for the determination of the spectral energy distribution of γ -ray sources with HAWC. Two energy estimation techniques are being used in HAWC analyses currently. The one applied in the analysis presented in this dissertation is described here. It is referred to as the ground parameter (whereas the other is an artificial neural network) [27]. It measures the charge at a particular distance 40

m from the reconstructed core location. The distance was tuned by the method described in [26]. The optimal distance is chosen to reduce the fluctuations in the LDF from the from the distance from the core [26]. Events are binned in 2-dimensional bins, one for energy assignment and another for angular resolution. The angular resolution bins are referred to as the f_{hit} bins described in [21]. The f_{hit} refers to the fraction of the PMT channels in array which are triggered in a particular event.

$\mathcal{B}$	f_{hit}	$\psi_{68}(^{\circ})$
1	0.067 – 0.105	1.03
2	0.105 – 0.162	0.69
3	0.162 – 0.247	0.50
4	0.247 – 0.356	0.39
5	0.356 – 0.485	0.30
6	0.485 – 0.618	0.28
7	0.618 – 0.740	0.22
8	0.740 – 0.840	0.20
9	0.840 – 1.010	0.17

Table 2.1

Table of f_{hit} bin boundaries with corresponding angular resolutions. Table taken from [21]

The energy is assigned in a two step process. First, the data is fit to a modified NKG function [26, 27],

$$\begin{aligned} \log(NKG) = \log_{10}(A) + s \cdot \left[\log_{10}\left(\frac{r}{124.21}\right) + \log_{10}\left(1 + \frac{r}{124.21}\right) \right] \\ - 3\log_{10}\left(\frac{r}{124.21}\right) - 4.5\log_{10}\left(1 + \frac{r}{124.21}\right) \end{aligned} \quad (2.12)$$

where r is the distance (in ground coordinates) to the reconstructed core, and the

amplitude A & s (proportional to the shower age) are the fit parameters.

Then a linear function is used to determine the energy,

$$\log(E) = m(\theta) \cdot \log(NKG) + b(\theta) \quad (2.13)$$

where m and b are linear functions of the zenith angle, whose appropriate values are determined from simulation of γ -ray EAS events. The energies are then binned logarithmically in quarter decade energy bins (Seen in Table 2.2) and assigned a letter label, from a-1 [27].

Energy bin	$\log_{10}(E/\text{GeV})$
a	2.50-2.75
b	2.75-3.00
c	3.00-3.25
d	3.25-3.50
e	3.50-3.75
f	3.75-4.00
g	4.00-4.25
h	4.25-4.50
i	4.50-4.75
j	4.75-5.00
k	5.00-5.25
l	5.25-5.50

Table 2.2
Energy bin boundary definitions

For example, an event triggering half (a fraction of 0.5) of the array with a reconstructed energy of 40 TeV would be assigned to bin 6i.

2.5 Analysis Procedure and Data points

Analysis of HAWC data is performed via a forward-folding procedure [21]. Simulations of data are performed, and distributions of simulated events which fall into each analysis bin are constructed. These distributions are contained in a detector response file. When a source is fit to data, the true values of different parameters are translated into the data that is measured by the HAWC array using the detector response file. These parameters are iterated upon to achieve the best possible agreement with data. This means that there is a sense in which the most fundamental measurement is the fit to the data that we perform, and data (hereafter also called flux) points are optional. A more detailed description of fitting can be found in Chapter 3. As an example, the distribution of energies reconstructed into each energy bin are shown in Figure 2.10.

To plot flux points, the flux in each energy bin is fit in that single energy bin. This gives the flux and uncertainty, but not the energy in which that uncertainty is measured. We plot the measured energy flux at the median energy in the true energy distribution for that bin. Due to the symmetric nature of the distributions about

Figure 2.10: The true energy distribution for each energy bin included in the final model for HAWC J2019+368 (here labeled as `hwc_J2019`). The final model is described at the end of Chapter 6 and discussed in Chapter 7.

their peak, the median energy in each energy bin is very nearly the peak in that bin shown in Figure 2.10.

It is possible that a source may be significantly detected over all energy bins, but not significantly detected in each individual energy bin. For low significance sources such as these, flux points are typically not shown. This may be thought of in two ways: the source is only significantly detected in the totality of the data, rather than the individual bins themselves, or the flux cannot be well measured in energy ranges

smaller than the energy range of the analysis itself.

Chapter 3

Fitting and Model Selection

Many of the basics of statistics may be found in a variety of texts. I personally find [30] to be particularly useful in this context. It is reasonable to start at the beginning.

Bayes Theorem may be usefully stated as:

$$P(\text{data} \mid \text{Model}(\theta_i)) = \frac{L(\text{Model}(\theta_i) \mid \text{data}) P(\text{Model}(\theta_i))}{P(\text{data})} \quad (3.1)$$

The $P(\text{Model}(\theta_i))$ term encodes our prior information about the model in question. There is *much* debate about this term, what priors to use, and whether to use a prior at all. The likelihood term $L(\text{Model}(\theta_i) \mid \text{data})$ quantifies how well our model fits to the data, and is in many ways the most important component of the theorem. This

term is computed and recomputed (in different ways depending on the details of a particular analysis) to find the parameters of a model which best fits the data. $P(data)$ is frequently treated as a normalization term and is sometimes referred to as the evidence [30, 31].

3.1 Fitting

The simplest kind of fitting is referred to as least squares fitting [30]. Given a model (defined by a function $f(x_i, \theta_i)$ and parameter(s) θ_i) for the data (given by x_i, y_i), the goal is to minimize the sum of the squares of the errors, S . This is expressed as,

$$S = \sum_{i=1}^N (f(x_i, \theta_i) - y_i)^2 \quad (3.2)$$

This function can be minimized many different ways, for simple models it can be minimized analytically by finding where the derivatives of θ_i are 0 and for a general model via a variety of numerical techniques, such as the Levenberg-Marquardt method [32]. A better fit can be frequently found however, by including information about the uncertainty in a particular set of measurements. Likelihood fitting accounts for the uncertainty (σ_i) in individual measurements when trying to find the parameters which best fit the model. To do this, we minimize the negative logarithm of the

likelihood (given by $-\mathcal{L}$),

$$\mathcal{L} = \sum_{i=1}^N \left(\frac{f(x_i, \theta_i) - y_i}{\sigma_i} \right)^2 \quad (3.3)$$

This method is named the maximum likelihood method [30]. The most likely set of parameters are the ones in the model which maximize the (log)likelihood (which is equivalent to minimizing the negative logLikelihood).

This can be derived assuming that each data point is drawn from a Normal distribution. If each data point is independent from the others, then the product of these is what is referred to as the likelihood of the model given the data. Because it is convenient, we take the logarithm of this to obtain a sum which is then readily usable. This algorithm weights the data appropriately, meaning pieces of data which are known more precisely are more important to the fit.

3.1.1 Fitting Example

In this example, we generate fake data along a line to demonstrate the two fitting methods; Least-Squares and Likelihood. The fake data is 10 random points in x and y . The x -axis values are drawn from a uniform random distribution between 0 and 20. The y -axis values are $y = 2x + 1$ plus a value drawn from a normal distribution $\mathcal{N}(\mu = 0, \sigma = 3)$ which is also taken to be the uncertainty. As seen in

Figure 3.1, the Likelihood fit achieved a closer fit to the “True” model than the Least-Squares method. Scientifically, this can be rephrased as better(or more precisely, more accurate) data contributes more toward understanding.

Figure 3.1: Using Least-Squares and Likelihood fitting to fake data to $y = 2x + 1$. The code to generate this plot can be found in Appendix A

3.2 Model selection

Once model fitting has been performed, we need to pick a model which we believe explains the data. In the example above 3.1.1, we might choose to compare a line model or a quadratic model. Nested models are models which have the property that setting one or more parameters of the model to 0 reduces that model to the other model. An important result, known as Wilk's theorem [33], states that the log-likelihood ratio for nested models (with likelihoods $L_{0/1}$ and log-likelihoods $\mathcal{L}_{0/1}$) will be χ^2 distributed. Typically this is referred to as the Test Statistic (TS). The TS is defined as,

$$TS = -2 \log \left(\frac{L_0}{L_1} \right) = -2 (\mathcal{L}_0 - \mathcal{L}_1) \quad (3.4)$$

For non-nested models, this result does not hold. In this case, the evidence ratio can be compared and used to compute the Bayes Factor (B_{ab}) under Laplace's Choice (no initial preference between the two models) to determine the best model [31]. The Bayes factor between models M_a and M_b with parameters θ_a and θ_b and prior parameter distributions $\pi(\theta_{a/b})$ may be computed by directly using the result from Equation 3.1 or taking the ratio of the evidence as:

$$B_{ab} = \frac{P(\mathbf{D}|M_a)}{P(\mathbf{D}|M_b)} = \frac{\int L(\mathbf{D}|\theta_a, M_a)\pi(\theta_a)d\theta}{\int L(\mathbf{D}|\theta_b, M_b)\pi(\theta_b)d\theta} \quad (3.5)$$

In practice, computing the Bayes Factor directly using Equation 3.5 is often computationally prohibitive. Instead different ways of approximating the Bayes Factor are used, such as the Akaike Information Criterion,

$$AIC = -2\ln(\hat{L}) + 2k \quad (3.6)$$

or the Bayesian information criterion,

$$BIC = -2\ln(\hat{L}) + k \cdot \ln(N) \quad (3.7)$$

where the number of parameters in the model is given by k , and the number of data points is N . These methods have the advantage that they are easy to compute, because they apply different penalties to the maximized logLikelihood $\hat{L}$, resulting in a model being required to “be that much better” to be preferred [30, 34]. In practice, you must compute the xIC for each model individually, and then the evidence against the model with the higher xIC is given as $2\ln(B_{ab})$ of Table 3.1.

$2\ln(B_{ab})$	B_{ab}	Evidence against M_b
0-2	1-3	Not worth mentioning
2-6	3-20	Positive
6-10	20-150	Strong
>10	>150	Very Strong

Table 3.1

Table of Bayes Factors reproduced from [31]

Chapter 4

Pulsar Powered Systems

Pulsar powered systems are those which are energetically driven by the spindown of a pulsar. This is distinct from the supernova shell, which is powering particle acceleration as it travels, distributing $\sim 10^{51}$ erg [18] into the surrounding environment. In comparison, a pulsar has much less energy ($\sim 10^{48} - 10^{49}$ erg [16]), but this energy is released via dipole radiation and particle production at a much slower rate than a spectacular supernova explosion. The regions energetically dominated by the spindown of these pulsars seems to extend to 10s of parsecs away from the pulsar [7].

Figure 4.1: Diagram of relative size of SNR, TeV Halo, and PWN (not to scale). Plot reproduced from [35]

4.1 Pulsars

Pulsars are the rapidly rotating neutron star core which remains after a supernova explosion [10, 16]. Their rotational energy forms the reservoir which powers the emission for the PWN and TeV halo which surrounds it. It has been observed that the pulsar slows down with time, this is referred to as the spindown. This spindown has been identified as primarily due to dipole radiation [16]. The primary observable

quantities for pulsars are their period and its time derivative (P & $\dot{P}$). Nearly all other quantities are derived using these values and assumptions about neutron stars. The rotational period is related to the angular frequency by $\Omega = 2\pi/P$. As the pulsar period decays, it follows [4],

$$\dot{\Omega} = -k\Omega^n \quad (4.1)$$

where n is the braking index. The value of n is usually assumed to be 3, because a rotating magnetic dipole emitting radiation loses energy proportional to Ω^3 [16, 36]. This can be experimentally measured, and typically has values between 2 and 3 [16, 36]. The braking index is important to understand the time dependence of other quantities. The spindown power, $\dot{E}$, can be derived from the kinetic energy of the pulsar, E , by

$$\begin{aligned} E &= \frac{1}{2}I\Omega^2 = \frac{1}{2}I\left(\frac{2\pi}{P}\right)^2 \\ \dot{E} &= 2\pi I \frac{d}{dt}(P^{-2}) = \frac{4\pi^2 I \dot{P}}{P^3} \end{aligned} \quad (4.2)$$

$\dot{E}$ is how quickly energy is being dissipated from the pulsar into its surrounding environment and I is the moment of inertia for a pulsar, usually taken to be 10^{45} g

cm² [4, 16]. Learning the age of the pulsar is a more difficult challenge, because it depends on the initial spindown period (P_0). The age of the pulsar is given by,

$$\begin{aligned}\tau &= \frac{P}{(n-1)\dot{P}} \left[1 - \left(\frac{P_0}{P} \right)^{n-1} \right] \\ \tau_c &= \frac{P}{2\dot{P}}\end{aligned}\tag{4.3}$$

This leads to the definition of the characteristic age, τ_c , assuming $n = 3$ and that $P_0 \ll P$ [16]. The surface equatorial magnetic field strength (B_{surf}) is given by,

$$B_{surf} = 3.2 \cdot 10^{19} \sqrt{P\dot{P}} \text{ G}\tag{4.4}$$

this leads to typical magnetic field strengths ranging from 10^8 - 10^{15} G. In [37], an equation for the potential due to the rotating magnetic fields were derived, and rewritten from [16],

$$\Delta\Phi = \frac{B\Omega^2 R_{NS}^3}{2c} \approx 6 \cdot 10^{12} \left(\frac{B_{surf}}{10^{12} \text{ G}} \right) \left(\frac{R_{NS}}{10 \text{ km}} \right)^3 \left(\frac{P}{1 \text{ s}} \right)^{-2} \text{ V}\tag{4.5}$$

Where R_{NS} is the radius of the neutron star. Goldreich & Julian [37] also derived the current associated with this potential drop. This current is the origin of the pulsar wind 4.6.

4.2 Pulsar Wind Nebulae

PWNe arise from the wind of electrons and positrons produced by the pulsar traveling outward [4, 16]. It is associated with the current, $\dot{N}_{GJ}$, given by

$$\dot{N}_{GJ} = \frac{B_{surf}\Omega^2 R_{NS}^3}{ce} \quad (4.6)$$

where e is the electron charge. PWNe are observed at a broad range of energies, and have different morphologies depending on the photon energies observed [4, 16]. Energy dependent morphology is useful to observe because it points toward the photons originating via electron and positron interactions because electrons cool on short timescales [10]. This limits the distance that electrons can travel from their source before losing much of their energy [38, 39]. Therefore, as observations are conducted at higher energies, the extent of the PWN will shrink.

4.3 TeV Halos

Understanding the spectrum and transport of electrons in our galaxy is critical to unraveling the positron excess measured by Pamela and AMS-2 [40, 41]. One possible explanation for this excess is Dark Matter. If the positron excess is due to Dark Matter, it is important to understand what contributions to that excess are made by local sources of positrons, such as the Geminga pulsar [6]. HAWC observations of the extended emission regions surrounding the Geminga and Monogem pulsars [6] claimed that these nearby pulsars can only explain a small fraction of the positron excess. This assumed a small “one-zone” of diffusion for high energy electrons and positrons. Assuming a “two-zone” model lead to the theoretical prediction that extended structures of slow diffusion may exist around other pulsars [7]. These first detections have been dubbed TeV Halos [7]. TeV Halos consist of electrons and positrons which have escaped the PWN, and have begun to propagate diffusively in the interstellar medium. Further work has predicted some properties [42] of these objects, although much work remains to be performed.

4.4 Electron Cooling

The term cooling refers to the generic loss of energy by electrons due to various processes [10], typically by IC or synchrotron radiation, which tend to be the dominant energy loss mechanisms at high energies. There are several cases of interest given in [43], which give the generic result that, a spectral break is produced in an electron spectrum due to accumulated synchrotron losses over time.

4.4.1 Synchrotron Energy losses

The total energy loss rate of an electron in a magnetic field is given by

$$-\left(\frac{dE_e}{dt}\right) = \beta(\theta)B^2E_e^2 \quad (4.7)$$

where B is the magnetic field, E_e is the energy of the electron, and $\beta(\theta)$ is a function proportional to $\sin^2(\theta)$ with θ being the angle between the magnetic field and the electron in motion [14, 43]. It is then simple to separate variables and integrate to obtain the result

$$E_e = \frac{E_0}{1 + t\beta(\theta)B^2E_0} \quad (4.8)$$

where E_0 is the initial energy of the electron. This shows that that for times $t > \beta(\theta)B^2E_0$ the energy of the electron in the field will decrease significantly.

4.4.2 Cooled Spectra

The electron (and positron) energy transport equation is defined by

$$\begin{aligned} \frac{\partial N(E, \theta, t)}{\partial t} = & Q(E, t) + D(E)\nabla^2 N(E, \theta, t) \\ & + \frac{\partial}{\partial E} [b(E, \theta)N(E, \theta, t)] \\ & + \frac{1}{2} \frac{\partial^2}{\partial E^2} [d(E)N(E, \theta, t)] \end{aligned} \quad (4.9)$$

The terms for diffusion ($D(E)$) and statistical acceleration (∂_E^2) are ignored for the present time, because we are only concerned with particle sources (Q) and energy losses ($b(E)$). The notation used here is taken from [14], and derived results are from [43].

4.4.2.1 No Particle Source

For a population of electrons distributed at $t = 0$ with $N(E, \theta, 0) = KE^{-\alpha}$ where K is the number of particles at a particular energy, Equation 4.9 is solved using,

$$\begin{aligned} b(E) &= \beta(\theta)B^2E^2 \\ Q &= 0 \end{aligned} \tag{4.10}$$

where B is the magnetic field, and E is the energy of the particle subject to synchrotron losses (with coefficients $\beta(\theta)$). For the case of particles normal to the magnetic field or having an isotropic distribution, respectively. For the case of the electron orientations normal to the magnetic field, the distribution $N(E, 0, t)$ is

$$N(E, 0, t) = \begin{cases} KE^{-\alpha} (1 - tbE)^{\alpha-2} & E < \frac{1}{bt} \\ 0 & E > \frac{1}{bt} \end{cases} \tag{4.11}$$

The particle spectrum presented in Equation 4.11 is largely only useful for illustrative purposes, but captures the behavior one expects, that after a certain amount of time, electrons above a certain energy will no longer be found in the population. For the more realistic case of the electron orientations with respect to the magnetic field being

isotropic, an integral over ϕ , θ is performed to remove the θ dependence in β , which is now called simply b . Then $N(E, \theta, t)$ is

$$N(E, \theta, t) = \begin{cases} 4\pi K E^{-\alpha} & E < \frac{1}{bt} \\ \frac{2\pi K E^{-\alpha-1}}{(\alpha-1)bt} & E > \frac{1}{bt} \end{cases} \quad (4.12)$$

The second case (Equation 4.12), might be found in a physical system in which no more electrons are being produced or accelerated, and the population of electrons is radiating its energy with time.

4.4.2.2 Particle Source

The inclusion of a source term,

$$\begin{aligned} b(E) &= \beta(\theta) B^2 E^2 \\ Q &= q E^{-\alpha} \end{aligned} \quad (4.13)$$

modifies the result slightly. The spectrum is given by,

$$N(E, \theta, t) = \frac{qE^{-\alpha-1}}{b(\alpha-1)} [1 - (1 - tbE)^{\alpha-1}] \quad (4.14)$$

$$\approx \begin{cases} 4\pi K E^{-\alpha} & E \ll \frac{1}{bt} \\ \frac{2\pi K E^{-\alpha-1}}{(\alpha-1)bt} & E \gg \frac{1}{bt} \end{cases} \quad (4.15)$$

In this case, at early times, the source term dominates the particle spectrum, while at later times the cooling is evident in the spectrum above a certain energy. This energy where the transition from $E^{-\alpha} \rightarrow E^{-(\alpha+1)}$ occurs is called the break energy. This type of system is likely to be found in many pulsars, where the observation of a break in the electron spectrum may provide information about the age and magnetic field of the system [9].

4.5 Electron Transport

A good understanding of how electrons propagate in our galaxy is key to understanding how they arrive at Earth. In this section, I present basic results of diffusive and advective processes relevant to electrons and positrons.

4.5.1 Diffusion

Closely following the derivation given in [13, 44], and ignoring advection, the differential equation describing the transport of electrons is given by:

$$\frac{\partial f}{\partial t} = \frac{D(E)}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial f}{\partial r} + \frac{\partial}{\partial \Gamma} (P(\Gamma) \cdot f) + Q \quad (4.16)$$

Here $f = f(R, t, \Gamma)$ which is the function describing the distribution of electrons at a particular time, t , and place r , having energy $\Gamma = E_\gamma/m_e c^2$. Γ is defined in multiples of electron masses. The function $P(\Gamma)$ describes the energy dependent energy loss rate, and $D(\Gamma)$ describes the energy dependent diffusion of the electrons having a source Q . This equation has been solved in a variety of contexts: for instantaneous injection, continuous injection from a point source, and continuous injection from uniformly distributed sources. These cases are given explicitly in [13]. Only the first two are presented here.

- Instantaneous injection with arbitrary spectrum $Q(\Gamma)$

$$f(r, t, \Gamma) = \frac{Q(\Gamma_t)P(\Gamma_t)}{\pi^{3/2}P(\Gamma)r_d^3} e^{-\left(\frac{r}{r_d}\right)^2}$$

- Continuous injection from a point source

$$f(r, \Gamma) = \frac{1}{8\pi^{3/2}P(\Gamma)} \int_{\Gamma}^{\infty} \frac{Q(x)dx}{[\Delta u(\Gamma, \Gamma_t)]^{3/2}} e^{-\left(\frac{r}{4\Delta u(\Gamma, x)}\right)^2}$$

where the parameters $r_d = 2\sqrt{\Delta u}$ and Γ_t are defined as the diffusion radius (r_d) for a particle with energy $\Gamma \rightarrow \Gamma_t$ over time t governed by Δu (Δu is related to the change in the energy of electrons over time). These equations formed the basis of the morphological analysis performed for the Geminga and Monogem pulsars by HAWC [6]. This form however is unhelpful for unknown sources distances and sizes. The function used in HAWC is converted for measured angular sizes,

$$f(\theta, E_{e\pm}) = \frac{1.22e^{-\frac{\theta^2}{\theta_d(E_{e\pm})^2}}}{\pi^{3/2}\theta_d(E_{e\pm})[\theta + 0.06\theta_d(E_{e\pm})]} \quad (4.17)$$

where θ_d is the diffusion radius measured in degrees, and E_e is the energy of the electrons. In the Supplementary materials for [6], a non-standard formula for converting the electron energy $E_{e\pm}$ to the γ -ray energy E_γ is found,

$$\langle E_{e\pm} \rangle \approx 17 \langle E_\gamma \rangle^{0.54+0.046 \log_{10}(E_\gamma/\text{TeV})} \quad (4.18)$$

This equation accounts for Thomson and Klein-Nishina scattering for mean electron

to mean γ -ray energy. Additionally, in [6] the Supplement contains the following equation:

$$\theta = \theta_0 \left(\frac{E}{E_0} \right)^{\frac{\delta-1}{4}} \quad (4.19)$$

It relates the diffusion exponent δ from $D(E) = D_0(E/E_0)^\delta$, which describes the energy dependent diffusion coefficient, to the angular size *theta* measured by HAWC at energy E_0 with extent θ_0 . The functional form, a power law describing the relationship between angular extent and energy, will be useful in the next section.

4.5.2 Advection

For advection, the relationship between radius and energy is somewhat simpler to write down. This result is outlined in [39], but the derivation is my own. Assuming mass continuity, you can write down the generic relationship between velocity (v) and radius (r) as,

$$v(r) = v_o \left(\frac{r}{r_o} \right)^{-\beta} \quad (4.20)$$

where β describes the relationship between the two. Separating the variables in

Equation 4.20 and integrating gives,

$$\int_0^R r^\beta dr = v_o r_o^\beta \int_0^{\tau_c} dt \quad (4.21)$$

From Section 2.2 in [10], the cooling time, τ_c , is $\propto E^{-1}$ therefore,

$$\begin{aligned} R^{\beta+1} &= C E^{-1} \\ R &\propto E^{\frac{-1}{\beta+1}} \\ R &= R_o \left(\frac{E}{E_o} \right)^{-\frac{1}{\beta+1}} \end{aligned} \quad (4.22)$$

These equations are derived for a flow of electrons with energies E . Converting to γ -ray energies E_γ , the Thomson regime gives $E_\gamma \approx E^2$ and the Klein-Nishina regime gives $E_\gamma \approx E$ [10].

4.6 Generalized Energy Dependent Morphology

Both diffusion, Equation 4.19 and advection, Equation 4.22 express the energy dependence of the electrons as a power law in energy. Using the same notation as Equations 4.19 and 4.22, the energy dependent morphology of a particular source may be parameterized as,

$$\theta = \theta_o \left(\frac{E}{E_o} \right)^{-\alpha} \quad (4.23)$$

Equation 4.23 is a generic way to probe the energy dependent morphology of any particular source in the sky without *a priori* choosing advection or diffusion models. This parameterization does not specify the shape of the emission, only its energy dependence, which may be any shape which has an extent parameter.

Chapter 5

A Multi-Wavelength View of HAWC J2019+368

This chapter will review the associated sources in the HAWC J2019+368 region in the sky, spanning from radio observations to TeV measurements by instruments other than HAWC. This is helpful to place the HAWC observations in the proper context.

5.1 PSR J2021+3651

PSR J2021+3651 was originally discovered as a followup to an unidentified EGRET source[45]. Its pulsar parameters are provided in Table 5.1 from [45, 46]. This is a

highly energetic pulsar, and due to its high spindown luminosity and PWN morphology it is said to be Vela-like [45–47]. Vela is used as a comparison because it is a highly energetic pulsar considered to be a prototype for young pulsar systems [48, 49].

Parameter (units)	Value	Uncertainty
Period (s)	0.103740952074	$4(10^{-12})$
Period Derivative (s/s)	9.57209×10^{-14}	$7(10^{-19})$
Spindown Luminosity (erg s^{-1})	$3.4(10^{36})$	-
Characteristic Age (kyr)	17.2	-
Distance (kpc)	1.8	$+1.7$ -1.4

Table 5.1

This table is a partial reproduction of Table 2 from [45], with updated information from [50]. The distance measurement is from [46] and is a 90% containment uncertainty.

5.1.1 Distance

Combining data from optical and X-ray observations, Kirichenko *et al.* were able to constrain the distance to PSR J2021+3651 significantly (seen in Table 5.1) [46]. Their measurement is taken to be the nominal distance for this analysis. Roberts *et al.* estimated the distance was > 10 kpc [45]. Further investigation in x-ray by Van Etten *et al.* estimated a distance from 3-4 kpc [47].

5.2 The Dragonfly Nebula

First reported by Hessels *et al.* using Chandra data, the spectral energy distribution of the Dragonfly Nebula has a spectral index of $\Gamma = 1.7^{+0.3}_{-0.2}$, consistent with Vela ($\Gamma = 1.7^{+0.3}_{-0.2}$) [51]. Followup observations were able to show a double torus morphology [47], leading to it being dubbed the “Dragonfly nebula”. Vela is the only other known PWN with a similar morphology [48, 49]. The torus-jet morphology in general is shared with other pulsars, such as the Crab, but the origin of tori are believed to be related to a large difference between the magnetic and spin axes [52]. For Vela and the Crab Pulsar Wind Nebulae, this angle difference is not well constrained [52]. A detailed understanding of the origin of this double torus structure remains elusive. An inner and outer nebula have been identified using X-ray measurements [47]. The inner nebula is approximately $20'' \times 10''$. The outer nebula is asymmetric, with the long end being approximately 0.2° in length. The edges of the outer nebula have a softer spectrum than the inner nebula, supporting the interpretation of the emission being due to a PWN consisting of electrons and positrons.

Using the Suzaku instrument, Mizuno *et al.* reported a morphology for the PWN of approximately $0.45^\circ \times 0.16^\circ$, with an orientation in agreement with VERITAS measurements [9, 53]. They also performed modeling of the underlying particle spectrum, explaining $\sim 80\%$ of the TeV flux to be originating from VER J2019+368 [9]. The

electron spectrum they considered was a broken power law spectrum with an exponential cutoff. The break energy was 80 TeV, with the index going from -2.1 to -3.1 before and after the break energy, respectively. The exponential cutoff was 1 PeV. The radiation fields considered were the CMB, and an infrared field with $T = 30$ K and an energy density of 0.3 eV cm^{-3} .

5.3 Sh 2-104

NuSTAR performed observations in this region, exploring the possibility that Sh 2-104, an HII region containing stellar clusters, was responsible for the emission from one side of VER J2019+367 which is spatially coincident with Sh 2-104 [54]. Instead it was determined to be more likely that this emission is associated with PSR J2017+3625. This makes it difficult to associate Sh 2-104 with any known TeV sources.

5.4 TeV Observations

Milagro first identified TeV emission in this region of the sky and designated it MGRO J2019+37 [55, 56]. A followup study showed MGRO J2019+37 had a hard spectrum

$(\alpha = 2.0^{+0.5}_{-1.0})$ with an exponential cutoff of 29^{+50}_{-16} TeV [57]. Its morphology was measured to be symmetric with a Gaussian extent of 0.7° . VERITAS followup measurements in 2014 showed an asymmetric Gaussian emission region with a major $\times$ minor axes of $0.34 \pm 0.03^\circ \times 0.13 \pm 0.02^\circ$ [53]. They measured a hard ($\alpha = 1.75 \pm 0.08$) spectrum up to almost 30 TeV. Further studies by VERITAS have left this measurement largely unchanged [58]. Significant effort was put into investigating multi-wavelength counterparts, pointing to the possibility of Sh 2-104 explaining at least part of the emission. Their interpretation is that the emission measured by VERITAS is primarily due to PSR J2021+3651. In the 2HWC catalog [11], the region was best fit by a disk with an 0.7° radius compared to a point source assumption. Owing to the larger energy range of HAWC compared to VERITAS [11, 53, 58], HAWC measured a softer spectrum. This indicates a softening of the spectrum at higher energies beyond the VERITAS energy range.

Chapter 6

Spectral and Morphological studies of HAWC J2019+368

This chapter details the analysis I performed on the region near 2HWC J2019+367.

Over the course of the analysis, I will show that two sources are responsible for the emission, naming them HAWC J2019+368 and HAWC J2016+371. For the final morphological and spectral model, skip to section 6.4.

6.1 General Analysis Description

Using 1038.75 days of data, I used the following analysis bins used to perform spectral and morphological studies: 1c, 1d, 1e, 2c, 2d, 2e, 2f, 3c, 3d, 3e, 3f, 4c, 4d, 4e, 4f, 4g, 5d, 5e, 5f, 5g, 5h, 6e, 6f, 6g, 6h, 7f, 7g, 7h, 7i, 8g, 8h, 8i, 8j, 9g, 9h, 9i, 9j, 9k, 9l. These bins are chosen for optimal sensitivity at this declination, and only correspond to reconstructed energies above 1 TeV [27]. Unless otherwise specified, the analyses are performed in a 3° Region Of Interest (ROI) centered at Right ascension, Declination (RA, Dec) = 304.8690° , 36.7710° ($l, b = 74.97267^\circ$, 0.331697°) this was chosen to attempt to minimize contamination from nearby known sources.

In several places $\Delta\text{TS} = -2(\mathcal{L}_0 - \mathcal{L})$ (Equation 3.4) is used to compare nested models, this follows Wilks theorem [33]. Elsewhere, BIC is used to perform model selection, In those cases, Table 3.1 is used to determine the evidence against the model with higher BIC.

6.2 Morphology

The morphology was examined assuming only power law spectral models (More details about spectral models can be found in Section 6.3). The exploration of the source

morphology starts with a one-source model, and moves to a model that includes a second source. The 2HWC catalog [11] found the position for 2HWC J2019+367 to be RA, Dec = 304.94° , 36.8° in a point source search, which is used for the fixed position models.

For these studies, σ refers to the Gaussian extent, RA & Dec are the Right Ascension and Declination (the position in the sky), a is the major axis extent, e is the eccentricity, and θ is the rotation angle relative to the position. The Gaussian shape is a simple symmetric 2D Gaussian on the sky. An Asymmetric Gaussian is a more generic 2D Gaussian function which may appear more ellipsoidal than circular.

6.2.1 One-Source Model

First, a one source study was performed. In the following, I describe the models that were tested. All models had free flux normalization and spectral index. All parameters other than those specified below are fixed.

- Gaussian shape: σ free
- Gaussian shape: RA, Dec, σ free
- Asymmetric Gaussian shape: a , e , θ free
- Asymmetric Gaussian shape: RA, Dec, a , e , θ free

The best fit shape of the morphology is chosen via BIC.

	fixed position	free position
Symmetric	133097.982870	133114.345482
Asymmetric	133041.244241	133060.577193

Table 6.1

One source BIC values for symmetric and asymmetric Gaussian models.
The values reported are the full log file output.

The full reported precision from the log files are reproduced in Table 6.1, whereas for model decision making the ΔBIC is rounded to an integer value. The asymmetric models are very significantly preferred with a ΔBIC of 57(54) for fixed(free) models.

The best fit position for the asymmetric model is $(\text{RA}, \text{Dec}) = (304.916^\circ \pm 0.025^\circ, 36.767^\circ \pm 0.012^\circ)$. More information about the shape of the fit is in Table 6.3. Looking at the residual maps for the asymmetric models in Figure 6.1, we find a $> 5\sigma$ excess located at $(\text{RA}, \text{Dec}) = (304.10^\circ, 37.22^\circ)$. This is 0.09° from the VERITAS reported position for VER J2016+371. The apparent excess very near the location of VER J2016+371 motivates the inclusion of a second source in the model.

(a) asymmetric fixed position model

(b) asymmetric fit position model

Figure 6.1: Significance maps after subtracting the one-source model specified in the subfigure caption. The green circle illustrates the ROI in which the fit was performed.

6.2.2 Two-Source Model

Testing models including a point source at the position (RA, Dec) = (304.10°, 37.22°) were considered next. This new source is designated HAWC J2016+371. After including HAWC J2016+371 in the model, the previous asymmetric models are then tested to check for a change in the spatial morphology of HAWC J2019+368, assuming a fixed and free position in the fit.

fixed position	free position	Δ TS
-66471.435381	-66466.786155	9

Table 6.2

The likelihood of the models fixing or fitting the position of HAWC J2019+368 in a model consisting of HAWC J2019+368 and HAWC J2016+371.

The fit position model is a better fit to the data than a fixed position model (by Δ TS=9). We proceed using the fit position as the nominal position of the course. This model is improved by the addition of an additional point source over the model consisting of only HAWC J2019+368 by Δ TS= 39, therefore this source is included and treated as a real γ -ray source for future studies. The full reported precision from the output log files are reproduced in Table 6.2, while the Δ TS is rounded to the nearest integer. The spatial parameters for HAWC J2019+368 between the fits including HAWC J2016+371 and not including HAWC J2016+371 are summarized in Table 6.3 below.

# Sources	RA (°)	Dec (°)	a (°)	e	θ (°)
1	304.916 ± 0.025	36.767 ± 0.012	0.378 ± 0.024	$0.949^{+0.016}_{-0.20}$	20.9 ± 2.7
2	304.925 ± 0.025	36.764 ± 0.012	0.375 ± 0.023	0.960 ± 0.015	22.0 ± 2.5

Table 6.3

Comparing One and two-source models on the best-fit parameters of the model. The model with one source corresponds to a model including only HAWC J2019+368. The model with two sources corresponds a model consisting of both HAWC J2019+368 & HAWC J2016+371.

From Table 6.3 you can see that the addition of HAWC J2016+371 to the model had the most impact on the rotation and eccentricity of the asymmetric Gaussian. The position shifted slightly, but this is expected considering the inclusion of an additional source in the model. For examining the background model we use the best fit position including HAWC J2016+371 and fit the rest of the shape parameters.

Looking at the residual maps for the asymmetric models in Figure 6.2, we no longer find an excess coincident with the source VER J2016+371. The residual histogram (Figure 6.3) for these models shows that the mean of the distribution is ~ 0.8 , whereas the expectation is that the mean should be near zero to be consistent with statistical fluctuations. A consistent excess of counts can also be seen in the ROI looking at the counts residuals (Figure 6.4). A model which is a “good fit” to the data should have the residuals distributed about zero, rather than having a clear skew in a positive or negative direction. This motivates an investigation of a background γ -ray source model, distinct from the cosmic-ray background, which is calculated via direct integration, and is what is usually referred to as background in any given HAWC

analysis. The goal is to move the mean and width of the distribution to $0 \pm \epsilon_0$ and $1 \pm \epsilon_1$ respectively.

6.2.3 Background Models

The background model is investigated in multiple ways. For the analysis of the background, we will use a source model consisting of HAWC J2019+368 and HAWC J2016+371 with fixed positions, fitting the remaining spatial and spectral parameters. The two background models examined here are as follows: a uniform background across the ROI, and a detailed background model consisting of the HAWC Cocoon, 2HWC J2006+341, and a disk on the lower portion of the ROI, hereafter referred to as the “blob” (This can be seen in Figures 6.8 and 6.10).

6.2.3.1 Uniform Background

To represent a uniform background, a source having a disk morphology with a 5° radius placed at the center of the ROI. The radius of the ROI is smaller than the radius of the background source, to ensure that the source is flat across the ROI. The model fit to the data then consists of the following three sources with these free parameters:

(a) asymmetric fixed position model

(b) asymmetric fit position model

Figure 6.2: Significance maps after subtracting the morphological model for HAWC J2019+368 specified in the figure caption. Note the difference between these and Figure 6.1 by including HAWC J2016+371 as a point source. The green circle illustrates the ROI in which the fit was performed.

(a) asymmetric fixed position model

(b) asymmetric fit position model

Figure 6.3: Significance histograms of the residuals map shown in Table 6.2.

- HAWC J2019+368: a, e, θ , flux norm, index
- HAWC J2016+371: flux norm, index
- Uniform Background: flux norm, index

The eccentricity and inclination are nearly the same between the two models within uncertainties, whereas the semi-major axis shrinks slightly, although not significantly. This is expected since the uniform background is likely to absorb some of the flux

(a) asymmetric fixed position model

(b) asymmetric fit position model

Figure 6.4: Binned counts residuals in the ROI. Bin labels correspond to the bins described at this beginning of the chapter.

	a (°)	e	θ (°)
No Background	0.375 ± 0.023	0.960 ± 0.015	22.0 ± 2.5
Uniform background	0.352 ± 0.022	0.968 ± 0.014	21.4 ± 2.5

Table 6.4

Comparing the spatial parameters before/after including a uniform background model

from the tails of the extended emission region from HAWC J2019+368. Seen in more detail in Table 6.4, the difference between the semi-major axis (a) including the uniform background is nearly the same as the uncertainty on the value itself. For

Source in Model	TS
HAWC J2019+368	912.4
HAWC J2016+371	28.1
Uniform Background	58.9

Table 6.5

TS of each source in a model consisting of HAWC J2019+368, HAWC J2016+371, and a uniform background.

the eccentricity and inclination the difference is smaller than the uncertainty. The significance of the sources in the model consisting of the two sources with a uniform background are in Table 6.5. Examining the residual histogram in Figure 6.5, we see much better agreement with a normal distribution centered near 0 with a width near 1. Despite sources at the edge of the FoV, there seem to be few obvious locations of over or under-subtraction in the ROI in Figure 6.6.

Finally, the counts residuals in Figure 6.7 dramatically improves compared to Figure 6.4. Now it appears about half of the bins are above and below the zero line, in the lower part of Figure 6.7. Despite being somewhat difficult to read, the outlier in bin 5f appears to be nearly incompatible with the fit. This is because it is expected that the residuals will be gaussian distributed, and 5σ deviation from that distribution would be evidence in favor of a newer model being required to explain the data. A curved spectrum for HAWC J2019 may bring the model into better agreement with the data for 5f.

Figure 6.5: Significance histograms of the residuals map shown in Table 6.6.

6.2.4 Detailed Background Model

This model consists of first accounting for known sources leaking into the ROI. This leakage can be seen in a map with 1° smoothing (Figure 6.8). It is apparent that there is significant ($> 5\sigma$) excesses leaking in from the cocoon region and 2HWC J2006+341. Additionally, there appears to be structure at the lower end of the ROI, which is the blob mentioned earlier. This will be discussed further in the next section.

Figure 6.6: Residual map of the region after subtracting HAWC J2019+368, HAWC J2016+271, and a uniform background model. The ROI is indicated with the green circle.

Figure 6.7: Binned Counts with residuals in the ROI including a uniform background model from the map shown in Figure 6.6. Bin labels correspond to the bins described at this beginning of the chapter.

6.2.4.1 Two Source Background Model

Including only the Cocoon and 2HWC J2006+341 as background sources accounts for approximately half of the difference from 0 seen in Figure 6.3. The histogram with a mean at ~ 0.4 rather than 0.8 is shown in Figure 6.9. In this model the Cocoon and 2HWC J2006+341 models were accounted for by including models from two collaborators on HAWC [59, 60]. The Cocoon is modeled as a 2D Gaussian

centered at Cygnus OB2. The model for 2HWC J2006+341 is a 2D Gaussian with a position fit seeded at the HAWC position from the 2HWC catalog.

Figure 6.8: Significance map of the Cygnus region.

6.2.4.2 Three Source Background Model

From Figures 6.9 and 6.10, it is clear to see that accounting for the leakage from 2HWC J2006+341 and the Cocoon only addresses the “top half” of the ROI. Adding a 3° disk at the approximate centroid of emission at $(l, b) = (74.07^\circ, -2.25^\circ)$, moves the residual histogram nearly to 0. In Figure 6.12 it appears leakage from the VER J2019+407 and TeV J2032+4130 may be present, but there does not seem to be

Figure 6.9: Significance map of the Cygnus region with 1° extended source smoothing.

strong evidence for that given the residual histogram in figure 6.11. The point source residual map in Figure 6.13 seems to show that what remains in the ROI is not significant. The TS of each source in the model seen in Table 6.6 shows moderate contributions from the Cocoon and 2HWC J2006+341, as well as the “blob” source.

This detailed background study indicates that the significant deviation of the residuals from 0 seen after subtracting HAWC J2019+368 and HAWC J2016+371 result from contributions from the HAWC Cocoon, 2HWC J2006+341 and the blob. The blob source appears to be localized to the bottom half of the ROI which is approximately

Figure 6.10: Significance map of the Cygnus region with 1° extended source smoothing after including 2HWC J2006.+341 and the Cocoon. The large region of positive excess in the lower portion of the ROI is the blob.

well fit by a disk morphology centered at $(l, b) = (74.07^\circ, -2.25^\circ)$. This “conspiracy of sources” results in the background being well described by a uniform disk model.

Source in Model	TS
HAWC J2019+368	881.1
HAWC J2016+371	33.7
Cocoon	14.6
2HWC J2006+341	13.8
“blob”	37.1

Table 6.6

TS of each source in a model consisting of HAWC J2019+368 and HAWC J2016+371 with background sources of the Cocoon, J2006 and the “blob”.

Figure 6.11: Significance Histogram of ROI after including a detailed background source model including 2HWC J2006+341, the Cocoon, and a 3° disk centered at $l, b=74.07^\circ, -2.25^\circ$.

Therefore for simplicity in the analysis, we shall prefer the uniform background model.

Figure 6.12: Significance map of the ROI with 1° extended source smoothing after including 2HWC J2006+341, the Cocoon, and the “blob”. The bright sources near the top of the plot, but not contained in the ROI, are the γ Cygni SNR and TeV J2032+4120

Figure 6.13: Significance map of the ROI with PSF smoothing after subtracting HAWC J2019+368, HAWC J2016+371, 2HWC J2006+341, the Cocoon, and the “blob”.

6.2.5 VERITAS Two-Source Model

In their 2018 paper [58], the VERITAS collaboration claimed the possibility of two morphologies explaining the emission from HAWC J2019+368. One possibility was an elliptical Gaussian model similar to that reported here, the other is a two-source model.

Source	σ_a ($^{\circ}$)	σ_b ($^{\circ}$)
HAWC J2019+368(this work)	0.368 ± 0.022	0.12 ± 0.02
VER J2019+368 (2018)	0.34 ± 0.02	0.14 ± 0.01
VER J2018+367	0.18 ± 0.01	–
VER J2020+368	0.03 ± 0.01	–

Table 6.7

Comparison of morphology between VERITAS and HAWC data. VER J2020+268 and VER J2018+367 are symmetric Gaussian sources, and do not have an additional spatial parameter other than the Gaussian width.

Checking this model requires us to keep in mind that the HAWC PSF is $\sim 0.1^{\circ}$. Therefore, we would anticipate seeing VER J2020+368 as a point source because its extent is smaller than the HAWC PSF. Testing the question of “Do we see the VERITAS morphology of VER J2020+368 and VER J2018+367 instead of VER J2019+368” then is as simple as fitting a a model corresponding to the VERITAS two source morphology. VER J2018+367 is modeled as an extended Gaussian source, and VER J2020+368 is modeled as a point source. Both sources had power law morphologies assumed. Looking at the residual map however (Figure 6.14), it appears as though there are significant residuals left over after the proposed VERITAS sources are accounted for. We therefore prefer the one-source model for the J2019 region, which is consistent with the VERITAS morphology of one source.

6.3 Spectrum

Three spectral models are now considered here: a power law

Figure 6.14: Significance map of the ROI after subtracting a source at the locations of VER J2020+368 and VER J20218+367.

$$\frac{dN}{dE} = A \left(\frac{E}{E_0} \right)^\alpha \quad (6.1)$$

, a log parabola

$$\frac{dN}{dE} = A \left(\frac{E}{E_0} \right)^{\alpha - \beta \cdot \ln(E/E_0)} \quad (6.2)$$

, and power law with an exponential cutoff

$$\frac{dN}{dE} = A \left(\frac{E}{E_0} \right)^{\alpha} e^{-\frac{E}{E_c}} \quad (6.3)$$

where A is the flux measured at energy E_0 , power law index is given by α , the curvature parameter is given by β , and the cutoff energy is given by E_c . The power law and power law with exponential cutoff models are motivated by diffusive shock acceleration [14]. A log parabola spectrum is motivated by its ability to well localize the energy of the inverse Compton peak well [61]. The morphological model used includes a uniform background source across the ROI, HAWC J2016+371, and HAWC J2019+368 with its position fixed to the best fit value from Table 6.3 but with the remaining parameters (a, e, θ) free.

Only the spectrum of HAWC J2019+368 is investigated beyond a power law spectrum, HAWC J2016+371 and the uniform disk model are fit with power law assumptions. The best fit spectral parameters of HAWC J2019+368 are shown in Table 6.8.

Model	Flux at 10 TeV $10^{-14} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$	α	β	E_c TeV
power law	2.86 ± 0.15	-2.191 ± 0.032	0	∞
cutoff power law	$4.7^{+0.5}_{-0.4}$	-1.67 ± 0.10	0	38^{+9}_{-7}
log parabola	$4.05^{+0.26}_{-0.25}$	-2.02 ± 0.06	0.29 ± 0.05	∞

Table 6.8

The spectral parameters for HAWC J2019+368 for various model assumptions ($E_0 = 10 \text{ TeV}$). The values given without uncertainties (0 and ∞) correspond to the values of the parameter required to achieve that model in a general model considering a log parabola and an exponential cutoff.

HAWC J2019+368 Assumption	Flux at 10 TeV $10^{-15} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$	α
power law	$2.5^{+0.7}_{-0.5}$	-2.29 ± 0.18
cutoff power law	$2.5^{+0.7}_{-0.5}$	-2.30 ± 0.18
log parabola	$2.6^{+0.7}_{-0.5}$	-2.32 ± 0.18

Table 6.9

The spectral parameters for HAWC J2016+371 for different model assumptions for HAWC J2019+368 ($E_0 = 10 \text{ TeV}$).

HAWC J2019+368 Assumption	Flux at 10 TeV $10^{-14} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$	α
power law	$8.5^{+1.5}_{-1.3}$	-2.69 ± 0.08
cutoff power law	$8.2^{+1.5}_{-1.3}$	-2.74 ± 0.09
log parabola	$8.2^{+1.5}_{-1.3}$	-2.75 ± 0.08

Table 6.10

The spectral parameters for the uniform background model for different model assumptions for HAWC J2019+368 ($E_0 = 10 \text{ TeV}$).

The Tables 6.9 and 6.10 show the results of the fit for HAWC J2016+371 and the uniform background under different spectral hypotheses of HAWC J2019+368.

As expected, the background model spectrum is not strongly dependent on the spectral model for HAWC J2019+368. Similarly the spectrum for HAWC J2016+371

HAWC J2019+368 Model Assumption	$-\log(\text{likelihood})$	BIC	ΔTS see caption	ΔBIC see caption
power law	66437.132461	132992.052782	0	55.94
cutoff power law	66407.663782	132946.202964	58.94	10.09
log parabola	66402.617726	132936.110852	69.03	0

Table 6.11

Model selection for the spectral shape of HAWC J2019+368. The $-\log(\text{likelihood})$ and BIC are reported to full precision from the output log files. The ΔTS and ΔBIC are calculated with respect to the power law value, and the log parabola value respectively.

varies slightly depending on the model for HAWC J2019+368, but not significantly so. Making a table of the logLikelihoods and BIC values, we can examine the question of which spectral model is preferred (Table 6.11).

In each case, a curved spectrum (cutoff or log parabola) is preferred over a pure power law model. Looking at the ΔTS , the log parabola offers a greater improvement over a power law assumption than a cutoff power law model, however providing a direct comparison between the two is impossible using Wilk's theorem. Using the ΔBIC we have strong to very strong evidence that the log parabola spectrum is preferred over a cutoff power law spectrum. Given this, I choose to report the log parabola spectrum.

The plot of the HAWC J2019+368 spectrum under different spectral assumptions is given in Figure 6.15.

Over most of the relevant energy range the log parabola and the cutoff power law SED are statistically compatible. The energy range of the plot corresponds to the width

Figure 6.15: The spectral energy distribution of HAWC J2019+368 under different spectral assumptions. The energy range plotted corresponds to the limits of the reconstructed energy bins. The labels refer to the spectral assumptions made for HAWC J2019+368

of the quarter-decade reconstructed energy bins (seen in Table 2.2). The spectral energy distribution of HAWC J2016+371 (Figure 6.18) and of the uniform background (Figure 6.19) are not appear to be strongly affected by the spectral model of HAWC J2019+368.

The Figures 6.17 and 6.16 provide an indication that we have a good understanding of our background within the ROI.

Figure 6.16: The residual histogram in the ROI for a log parabola assumption for HAWC J2019+368

Looking at Figure 6.20 we can see that this model is a well-fit to the data in each bin. The largest difference is in bin 5f, where the data is $\sim 3\sigma$ away from the model in counts space, the other bins seem to be distributed about zero. Additionally, the flux points for HAWC J2019+368 should be reported. You can see the SED for HAWC J2019+368 and the flux points in Figure 6.21. We have a significant detection in bin k, and not in bin l.

The remaining Figures: 6.18 and 6.19 show how the spectrum of the background and HAWC J2016+371 change under different assumptions for HAWC J2019+368. Figure

Figure 6.17: The residual map in the ROI for a log parabola assumption for HAWC J2019+368

6.21 shows the significance of each flux point in the spectrum for HAWC J2019+368.

Figure 6.20 shows the counts residuals, showing that the model falls within 3σ of the data across all bins, this indicates good agreement with the data, and an improvement

compared to Figure 6.7.

Figure 6.18: The spectral energy distribution of HAWC J2016+371 under a power law assumption. The labels refer to the spectral assumptions made for HAWC J2019+368. The energy range plotted corresponds to the limits of the reconstructed energy bins (See Table 2.2).

6.4 Final Model

The nominal model is one consisting of a uniform background with a power law spectrum, HAWC J2016+371 as a point source with a power law spectrum and HAWC J2019+368 as an asymmetric Gaussian source with a log parabola spectrum. As

Figure 6.19: The spectral energy distribution of the uniform background under a power law assumption. The labels refer to the spectral assumptions made for HAWC J2019+368. The energy range plotted corresponds to the limits of the reconstructed energy bins (See Table 2.2).

shown in Figure 6.17 the residual map is free of any obvious significant hotspots.

6.4.1 Energy Range of the Flux Measurement

Finally, we examine the energy range over which our measurements of the flux are valid. The energy range over which the fit does not significantly change is a natural description of where to quote the flux. We do this by profiling the likelihood of the

Figure 6.20: The bin counts and counts residuals per bin in the ROI for a log parabola assumption for HAWC J2019+368. Bin labels correspond to the bins described at this beginning of the chapter.

best fit spectrum multiplied by a step function for each source in our model. For each source, we compute the likelihood of the model at a variety of grid points in energy. We define the range over which we confidently measure flux for a specific source by the energy value where the $\Delta\text{TS}=1$ between the likelihood with the step function at that energy and the model without the step function. In this case, we are claiming HAWC J2019+368 and HAWC J2016+371 to be sources in our model, whereas the uniform background serves as an approximation to emission from at least 2 other sources in the ROI. From the output of the script which generated it, and shown in

Figure 6.21: The spectrum and flux points for HAWC J2019+368. 90% upper limits are shown when $\sqrt{TS} < 2$ in that bin.

Figure 6.22, I report the flux between 2 and 138 TeV for HAWC J2019+368. For HAWC J2016+371 I report the flux between 2 and 40 TeV based on Figure 6.23. The uniform background model is not a single physical source, and so it makes little sense to examine the energy range of something that is not a useful physical measurement.

(a) Lower energy Range for HAWC J2019+368

(b) Upper energy Range for HAWC J2019+368

Figure 6.22: Results of the study used to determine the reported flux range for HAWC J2019+368 (See Section 6.4.1 for details).

(a) Lower energy Range for HAWC J2016+371

(b) Upper energy Range for HAWC J2016+371

Figure 6.23: Results of the study used to determine the reported flux range for HAWC J2016+371 (See Section 6.4.1 for details).

Chapter 7

Interpretation of HAWC observations

Now that a final model has been defined, we will compare it to other measurements, in particular VERITAS, which has overlap with the HAWC energy range.

7.1 HAWC J2016+371

The flux measured by HAWC appears largely consistent with that measured by VERITAS, although the HAWC measurements have extended the spectrum to higher energies. The low significance of HAWC J2016+371 in this analysis makes detailed

interpretation difficult, but there may be some evidence for softening in the spectrum (see Figure 6.23) at higher energies. To say much more, new data and/or a more detailed background model may be required. For now, we interpret the emission for HAWC J2016+371 to be the same as VERITAS, primarily due to the SNR CTB 87, with possible contributions from QSO J2015+371 [58]. The index measured by HAWC is $\alpha = -2.32 \pm 0.18$, which is compatible with the VERITAS measured index ($\alpha = -2.1 \pm 0.8$). This is the first independent detection of a source coincident with VER J2016+371 since its observation by VERITAS [62, 63].

Figure 7.1: The spectrum of HAWC J2016+371, compared to the flux measured by VERITAS [58]

7.2 HAWC J2019+368

The flux measured by HAWC is shown in Figure 7.2.

Figure 7.2: The spectrum of HAWC J2019+368, compared to the flux measured by VERITAS [58]

It is important to note the difference between the HAWC and the VERITAS flux measurements in the overlapping energy region. Not only that, but the VERITAS flux is different depending on if you look at the publication from 2014 or 2018 [53, 58]. Analysis differences between the two experiments largely explains the difference

in the measured flux. In this dissertation, the spectrum and morphology are fit simultaneously, so the flux reported corresponds to the entire source morphology in an ROI of 3° radius. VERITAS, and other IACTs, fit the morphology and spectrum separately. The spectrum is measured in an extraction region, which does not automatically correspond to the morphology of the source. In their 2014 paper, the VERITAS Collaboration used a larger 0.5° extraction region, whereas for the 2018 paper, a 0.23° region was used. A comparison of the extraction regions to the overall morphology measured by VERITAS is shown in Figure 7.3.

The smaller integration region (shown in Figure 7.3) does not fully enclose the 1σ region, which encloses $\sim 40\%$ of the total emission. The emission missed from the extraction regions explains the difference between the HAWC and VERITAS flux measurements. Scaling the VERITAS measurements by the fraction of the morphological shape not contained in the extraction region gives better agreement with the HAWC measurements. Put another way, this is a scaling of the flux to the measured morphology, assuming no energy dependent morphology. The scale factor for the 2018(2014) paper is $\sim 2.7(\sim 1.2)$. Scaling by this value gives Figure 7.4.

After scaling the VERITAS flux points to the VERITAS morphology, the flux measured by HAWC compares well with [58]. Checking the final model using the artificial neural network (the alternative energy estimator used in HAWC) gives similar results, although for this comparison, the neural network energy range study is not performed.

Figure 7.3: The normalized morphology reported by VERITAS with extraction regions and 1σ contour [58]. The integration regions used by the VERITAS Collaboration publications from 2014 (larger, 0.5° red dashed/-dotted circle) and 2018 (smaller, 0.23° red dashed circle) [53, 58]. The ellipsoid (in black) corresponds to the 1σ region of the VERITAS reported morphology.

An inverse compton spectrum is fit to the data using `naima` [64, 65], a software package which allows the fitting of an electron spectrum to the HAWC γ -ray data. The spectrum is a broken power law with exponential cutoff, similar to that used by Mizuno *et al.*, fitting the normalization and the exponential cutoff [9]. Integrating over the spectrum, it is possible to determine that the energy in the electrons in this spectrum above 1 MeV is $(3.6 \pm 0.3) \cdot 10^{47}$ erg. The total energy budget assuming

Figure 7.4: The spectrum of HAWC J2019+368, compared to the flux measured by the VERITAS Observatory [53, 58]. The analysis presented here is cross-checked using neural network maps (green dashed spectrum). Additionally, an inverse Compton spectrum is fit to the HAWC data points with the 68% containment band on the spectrum plotted.

constant spindown over the characteristic age of the pulsar is $1.98 \cdot 10^{48}$ erg, therefore the energy in electrons constitutes $\sim 18\%$ of the total spindown energy budget for the pulsar. The cutoff in the electron spectrum is $\log_{10}(cutoff/\text{TeV}) = 2.14 \pm 0.07$. This corresponds to a central value of 138 TeV. Using Equation 1.8, (which is taken from [9]), electrons at this energy are typically producing γ -rays of approximately 60 TeV. Taking the upper range of significantly measured flux, with γ -ray energies from 100-138 TeV, this means that we are directly observing electrons with energies

from 170-200 TeV. This is independent of knowledge or assumptions about the local magnetic field, which observations of synchrotron radiation are heavily dependent on.

The morphology measured in this analysis using HAWC data compares very well with the morphology measured by VERITAS. In table 7.1, we can see the similarity in the morphology. This is a compelling argument for both instruments to be measuring the same emission, regardless of its interpretation.

Source	Major axis ($^{\circ}$)	minor axis ($^{\circ}$)
HAWC J2019+368 (this work)	0.368 ± 0.022	0.12 ± 0.02
VER J2019+368 [58]	0.34 ± 0.02	0.14 ± 0.01

Table 7.1
Comparison of morphology between VERITAS and HAWC data.

7.3 Conclusions

In this thesis, I have shown a detailed morphological and spectral studies of the region surrounding HAWC J2019+368. In the process of data analysis, I revealed a source known in TeV, but unseen by HAWC until now, HAWC J2016+371. The spectrum and apparent point source morphology of HAWC J2016+371 agree with previous measurements by the VERITAS Observatory, and is likely attributable to the SNR CTB 87 [58]. The spectrum and morphology of HAWC J2019+368 show remarkable agreement with analyses shown by the VERITAS Collaboration, after accounting for

differences in the size of the extraction region and ROI of the respective analyses. The result presented in this thesis expands the measured energy range for this source to up to nearly 140 TeV allowing to constrain the γ -ray flux suppression at very high energies with unprecedented accuracy. I fit the γ -ray spectrum with a realistic electron spectrum and show that the HAWC data is able to explain the γ -ray emission from HAWC J2019+368 as the inverse Compton scattering of electrons up to 200 TeV.

Looking forward, new instruments such as SWGO and LHAASO are expected to show dramatic improvement over HAWC in sensitivity to the highest energy γ -rays [66, 67]. It is possible that these new instruments will be able to observe energy dependent morphology for this and other pulsar powered systems, solidifying the interpretation of the γ -ray emission originating via inverse Compton scattering. Finally, in the near future, the addition of data from a sparse outrigger array of ~ 300 small WCDs will significantly increase the size of the effective area of the HAWC observatory and improve the HAWC sensitivity to gamma-rays above 50 TeV by a factor of ~ 3 [68, 69]. These highest energy measurements will be crucial to understanding the limits of particle acceleration for pulsar powered systems and other kinds of systems in our universe.

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Appendix A

Code For Line Example

A.1 linear_example.py

```
import numpy as np
import matplotlib.pyplot as plt
import numpy.random as random
from scipy.optimize import curve_fit

def line(x,m,b):
    return m*x+b

#set it up
num_points = 10
low = 0
high = 20
```

```

b_true = 1
m_true = 2

random.seed(81)

#Generate Data
random_x = np.sort(random.uniform(low,high, size=num_points))
random_y = m_true*random_x+b_true
errors_y = 3*random.normal(size=num_points)
random_y += errors_y

#set x values for plotting
x = np.linspace(low,high,100)
seed_m = 0
seed_b = 0

#least squares fit
params = curve_fit(line, random_x, random_y, p0=[seed_m, seed_b], sigma=None)[0]
plt.plot(x,params[0]*x+params[1], label="Least Squares Fit", ls='-.')

#likelihood fit
params = curve_fit(line, random_x, random_y, p0=[seed_m, seed_b], sigma=errors_y)[0]
plt.plot(x,params[0]*x+params[1], label="Likelihood Fit")

# True Model
plt.plot(x,m_true*x+b_true, label="True Model", ls='--')

```

```
#the data
plt.errorbar(random_x,random_y, yerr=errors_y, fmt='o', ←
             markersize=3, color='k', label="Data")

plt.legend()
plt.savefig("line_example.pdf")
```