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STUDY OF THE CYGNUS REGION WITH FERMI AND HAWC

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STUDY OF THE CYGNUS REGION WITH FERMI AND HAWC

By

Andrew Robare

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Physics

MICHIGAN TECHNOLOGICAL UNIVERSITY

2018

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This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Physics.

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Preface

Section 7.5 makes use of the analysis of HAWC data by Binita Hona. She produced the energy spectrum and significance maps of the HAWC counterpart to the Fermi-LAT cocoon. She additionally helped write the description of the HAWC analysis in this section.

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Abstract

The Cygnus Cocoon is an extended source of high-energy gamma-ray emission in the Cygnus region. The gamma-ray emission has been attributed to a volume 50pc in diameter of freshly-accelerated particles near the Supernova Remnant γ Cygni which is located 1.4kpc from the solar system [Ackermann et al., 2011], [Tibaldo et al., 2013]. Since its discovery in 2011, Fermi LAT has improved their event reconstruction to allow analysis at higher energies, and recorded six additional years of data. An analysis was performed on the entire dataset to reproduce the previous results, then expand on them with higher energies and larger time spans of data. No evidence of temporal variability was found for the Cocoon. It was found that for the energy range of 1-870 GeV a logparabola spectrum is preferred over a powerlaw spectrum. Analysis is then done comparing the Cocoon spectrum measured using LAT data with a HAWC source [Hona et al., 2017] that is thought to be the Cocoon. It was found that the LAT powerlaw spectrum connects with the HAWC spectrum at 1 TeV, while the LAT powerlaw spectrum is an order of magnitude lower than the HAWC source. This means that for the combined analysis the powerlaw spectrum is preferred over the logparabola, if the HAWC source is the Cocoon.

Chapter 1

Introduction

The Cygnus Cocoon is an extended source of gamma-ray emission located in the Cygnus region on the Galactic plane. The Cocoon was first discovered in 2011 with data from the Fermi-LAT gamma-ray observatory. The gamma-ray emission from the cocoon is attributed to a 50pc across volume of freshly-accelerated particles. The origin of the cosmic rays in the Cocoon is considered to be the OB association Cygnus OB2. The cosmic rays are thought to be predominantly protons. In the Cocoon the protons interact with interstellar gases to produce neutral pions (π^0), which then decay into pairs of gamma rays. [Ackermann et al., 2011]

The gamma-ray signal from the Cocoon allows for the study of the cosmic-ray acceleration in star-forming regions like Cygnus OB2. There are a dozen star forming

regions similar to the Cygnus OB2 in the galaxy. A better understanding of the acceleration of cosmic rays in star-forming regions would improve analysis of these regions. Combined analysis of the spectrum found with both Fermi-LAT and HAWC for the Cocoon would allow for the study of higher-energy protons.

Since the discovery of the Cocoon in 2011, the Fermi-LAT collaboration has improved their event reconstruction to allow analysis at higher energies, and recorded six additional years of data. This will allow the analysis of the Cocoon at energy ranges from 100 GeV to 870 GeV. With analysis at higher energies than in the previous study it will be possible to compare the LAT Cocoon emission with a source found with HAWC data (1 to 100 TeV) that is thought to be the Cocoon.

For this thesis an analysis is performed using a 2 year LAT dataset to reproduce the previous results to confirm that with the updated data the Cocoon has not changed in location or energy spectrum density. It is found that the Cocoon is at the same location and has the same energy spectrum density. Then analysis is done with 8 years of LAT data to expand on the previous results. It is found that at energies above 100 GeV the energy spectrum is significantly below the extrapolation of the powerlaw previously found for the Cocoon. A logparabola energy spectrum for the Cocoon is found to be preferred over the powerlaw for the energy range 1-870 GeV.

A study is done to determine if the Cocoon could be detected in data from the HAWC observatory. If combined analysis of data from both the Fermi-LAT and

HAWC observatories could be done it would allow for study of the Cocoon from 1 GeV to 100 TeV. If the Cocoon's powerlaw spectrum extends to 100 TeV, there will be sufficient flux for HAWC to detect it. If the Cocoon's logparabola spectrum extends to 100 TeV, there will not be sufficient flux for HAWC to detect it. Analysis is then done comparing the Cocoon spectrum measured using LAT data with a HAWC source [Hona et al., 2017] that is thought to be the Cocoon. It is found that the LAT powerlaw energy spectrum connects with the HAWC powerlaw energy spectrum at 1 TeV, through the HAWC spectrum is softer. However, the LAT logparabola energy spectrum is an order of magnitude lower at 1 TeV compared to the found HAWC energy spectrum.

This thesis is organised as follows. Chapter 2 introduces gamma-ray production mechanisms and gamma-ray sources that are significant in the region and energy range analyzed in this thesis. In Chapter 3, the Cygnus region is introduced, along with the gamma-ray sources found there. Additionally the current understanding of the Cygnus Cocoon is summarized. Chapter 4 describes space and ground based detection methods for gamma rays, along with detailed descriptions of the Fermi-LAT and HAWC observatories. The analysis methods used in this thesis are described in Chapter 5.

Chapter 6 has a reproduction of Cocoon analysis with 2 years of LAT data. This is done to check that improvements to LAT data analysis methods have not significantly

changed the shape or spectrum measured for the Cocoon. The results of the analysis done for this thesis are presented in Chapter 7. This includes study of the Cocoon with 8 years of LAT data, study of the temporal variability of the Cocoon, and the reason that analysis of the Cocoon with LAT data is not done outside the 1-870 GeV energy range. Additionally the viability and the results of studying the Cocoon with the HAWC observatory is discussed. The last chapter summarizes the results of this thesis.

Chapter 2

Gamma Rays

Gamma rays are highest energy photons with an energy >100 keV. The highest energy gamma rays that have been detected have energies of ~ 100 TeV. The spectrum of mesued gamma-ray sources have non-thermal spectra at gamma-ray energies. As can be seen in Figure 2.1 the required temperature for an object to emit gamma-rays would be $\gg 10,000,000^\circ$ C for an object to emit gamma rays by blackbody radiation.

Figure 2.1: The electromagnetic spectrum (credit: phys.libretexts.org 16.5: The Electromagnetic Spectrum)

In addition to photons at gamma-ray energies there are cosmic rays. Cosmic rays are charged particles such as electrons, protons, and atomic nuclei. At high energies Cosmic rays greatly outnumber gamma-rays. At > 1 TeV the ratio is around 10,000 cosmic rays per gamma-ray. Cosmic-ray paths are affected by magnetic fields that they pass by, while gamma rays follow a straight path from their source. This can be seen in Figure 2.2 and means that for studying a distant object gamma-rays are preferable over cosmic rays. Additionally, cosmic rays can create gamma rays by means of Bremsstrahlung radiation, inverse compton scattering, and neutral π^0 decay.

Figure 2.2: Comparison of Photon, Neutrino and Cosmic-ray paths (credit: HAP / A. Chantelauze)

Gamma-Ray Production Mechanisms

There are four primary production mechanisms for gamma rays: synchrotron radiation, bremsstrahlung radiation, inverse compton scattering, and neutral π^0 decay. Synchrotron radiation is dominant at energies less than 100 MeV, not the GeV to TeV energy range in this study and is not discussed here. The other three production mechanisms are described in more detail in this section.

Supernova remnants (Section 2.2.1) and OB associations (Section 2.2.3) produce

gamma rays through bremsstrahlung radiation, inverse compton scattering, and neutral π^0 decay. Pulsars and pulsar wind nebula (Section 2.2.2) produce gamma rays primarily through inverse compton scattering. For the Cygnus Cocoon, π^0 decay is thought to be the primary gamma-ray production mechanism as discussed in Section 3.1.

Bremsstrahlung

When an electron passes near a charged particle (such as an atomic nucleus or proton) it is decelerated/accelerated by electromagnetic interactions. Some of the change in energy is released as photons while the remainder is exchanged with the charged particle. This process is called Bremsstrahlung radiation, or Braking radiation, and primarily occurs when electrons pass through clouds of interstellar gas. Additionally this occurs in the atmosphere and is a part of the air shower process (Section 4.3). [Sparke and Gallagher, 2007]

Figure 2.3: Illustration of Bremsstrahlung radiation produced by an electron passing near a hydrogen nuclei (credit: NASA/CHANDRA/S.Lee)

Inverse Compton Scattering

Inverse Compton Scattering is an interaction between a low energy photon and a high energy electron, resulting in the photon gaining energy while the electron loses energy. The original photon may be from the Cosmic Microwave Background or other sources. [Griffiths, 2014]

Figure 2.4: Illustration of Inverse Compton Scattering (credit: NASA/CHANDRA/S.Lee)

Neutral Pion Decay

This process occurs when a neutral pion (π^0) decays into two gamma-rays at the end of its lifetime of 8.4×10^{-17} seconds. Neutral pions are created for example when a cosmic ray collides with part of the interstellar medium, often atomic Nuclei. The collision produces charged pions ($\pi^\pm$) and neutral pions. [Ackermann et al., 2013]

Figure 2.5: Neutral pion decaying into a pair of gamma-rays [Miskimen, 2011]

Gamma-Ray Sources

The types of gamma-ray sources of interest in this thesis are Supernova Remnants, Pulsars/ Pulsar Wind Nebula, and OB associations. These sources generate high energy cosmic rays that then through the process described in the previous section generate gamma rays. The Supernova remnant γ Cygni is a significant source that is located near the Cygnus Cocoon as can be seen in Figure 3.2. There are two pulsars and pulsar wind nebula within the 2° 68% containment radius of the Cocoon (Appendix B.1). The OB association Cygnus OB2 is considered to be the most likely sources of the freshly generated Cosmic rays that produce the gamma rays in the Cygnus Cocoon as described in Section 3.1.

Supernova Remnants

When a star with a mass of $M_{\star} > 8 M_{\odot}$ reaches the end of its life (Type II), or a White dwarf reaches the Chandrasekhar limit of $\sim 1.4 M_{\odot}$ (Type Ia) a supernova explosion will occur. A Type II supernova occurs when the star's core finishes fusing all its material into iron, this results in the outer shell collapsing onto the core, compressing it until its neutrons become degenerate. This results in the core becoming rigid and causes the shell to bounce off the core and be ejected. A Type Ia supernova occurs when the white dwarf star exceeds a mass of $\sim 1.4 M_{\odot}$ by taking mass from a companion star it will collapse, which causes the star to begin fusion and explode. A supernova instantaneously releases $\sim 10^{51}$ erg of energy. More than 99% of the energy released will be in the form of neutrinos, while the remainder will be released in the form of kinetic energy by accelerating stellar material.[Sparke and Gallagher, 2007]

The stellar material travels at faster than the speed of sound in the material ($\sim 1,000 \text{ km s}^{-1}$) into the interstellar medium. The interstellar medium is compressed and heated by the forward shock front (As seen in Figure 2.6). This compressed interstellar and solar material forms a Supernova remnant. One of the best known Supernova Remnants is the Crab as seen in Figure 2.7.

Figure 2.6: Supernova explosion in the process of creating a Supernova Remnant <https://heasarc.gsfc.nasa.gov/docs/objects/snrs/snrstext.html>

Charged particles (electrons and protons) are accelerated by the shock front of the Supernova Remnants through the mechanism of First Order Fermi Acceleration. These charged particles then can generate gamma-rays through Inverse compton scattering (electron), Bremsstrahlung (electron) or Neutral pion decay (protons).

Figure 2.7: Crab Supernova Remnant, taken in visible light by the Hubble Space Telescope (credit: NASA,ESA)

Pulsars and Pulsar Wind Nebula

When a star with a mass $8 M_{\odot} < M_{\star} < 25 M_{\odot}$ or a star with very high metallicity and masses of $25 M_{\odot} < M_{\star}$ reach the end of its life and goes supernova, a neutron star will be created. If there is sufficient angular momentum and a correctly aligned rotational axis the neutron star will be a pulsar. [Heger et al., 2003]

As Pulsars rotate they spin a very strong magnetic field. This rotating field accelerates

Figure 2.8: Crab Pulsar Wind Nebula in x-ray taken with the Chandra Observatory (credit: NASA/CHANDRA/SAO)

charged particles from the surface of the star into space. The particles create the Pulsar Wind Nebula (PWN) that surrounds a Pulsar. The energy emitted in the form of charged particles and photons, $\sim 99\%$ of the emitted energy is charged particles, is taken from the rotational energy of the pulsar. Due to the emission the pulsar will spin down until it slows enough to no longer emit in the radio spectrum, this is expected to take 10-100 million years.[Kargaltsev et al., 2015]

The charged particles in the PWN interact with photons through Inverse Compton scattering to create gamma-rays. PWNe have been observed to create gamma rays into the TeV range. [Kargaltsev et al., 2015] This process is shown in Figure 2.9.

Figure 2.9: Diagram of a PWN, the Inverse Compton Scattering takes place in the wind acceleration zone [Aharonian et al., 2012]

OB Associations

OB Associations are star forming regions with 10-100 O and B spectral class stars, along with hundreds or thousands of smaller stars. Due to the short lives of O and B stars OB associations only last tens of millions of years. [Sparke and Gallagher, 2007]

In OB Associations such as Cygnus OB2 (around 100 OB type stars) gamma rays are produced in the shock areas where the stellar winds of multiple O or B stars interact. The primary gamma-rays production mechanisms in OB associations by inverse compton scattering, bremsstrahlung, and π^0 decay. [Benaglia et al., 2001]

Figure 2.10: Composit image of Cygnus OB2 in X-ray(blue), Infrared(red), and Optical(green). (Credit: X-ray: NASA/CXC/SAO/J.Drake et al, Optical: Univ. of Hertfordshire/INT/IPHAS, Infrared: NASA/JPL-Caltech) <http://chandra.harvard.edu/photo/2012/cygob2/>

Chapter 3

The Cygnus Region

The Cygnus region is an active star forming region on the Galactic plane, and is shown in Figure 3.1. Fermi-LAT has detected more than 60 gamma-ray sources in the Cygnus region [Acero et al., 2015]. The gamma-ray sources include 19 supernova remnants [Uyaniker et al., 2001], > 14 pulsars/ pulsar wind nebula [Manchester et al., 2005], Wolf-Rayet binary systems, microquasars, OB associations [Uyaniker et al., 2001].

(a) Fermi-LAT 9-year all-sky photon counts map ($>1\text{GeV}$) with the Cygnus region marked. The map is in Galactic coordinates.

(b) HAWC 30 months all-sky Significance map with the Cygnus region marked. The map is in Galactic coordinates.

Figure 3.1: Fermi-LAT and HAWC view of the Galaxy.

The Cygnus Cocoon

The Cygnus Cocoon is a volume of freshly accelerated cosmic rays in the Cygnus region near the star γ Cygni. A study of Fermi-LAT data revealed gamma-ray emission from a volume 50pc across that did not correspond to any known source. The Cocoon can be seen between the γ Cygni SNR and the Cygnus OB2 OB association in Figure 3.2. [Ackermann et al., 2011]

Figure 3.2: Smoothed photon counts map of the Cocoon region for 10-100 GeV with all other known sources subtracted. The black circles mark γ Cygni and Cyg OB2. (Figure from [Ackermann et al., 2011])

That study [Ackermann et al., 2011] looked at the Cygnus region using two years of Fermi-LAT data in the energy range of 0.1-100 GeV. It is found that the Cocoon was easily detectable above 1 GeV. Below 1 GeV the emission from the Cocoon is indistinguishable from the diffuse emission caused by interactions of the cosmic-ray sea with the interstellar medium.

In Figure 3.3, a photon counts map of the Cocoon is shown for the energy range of 10-100 GeV. Even after all known sources are subtracted, there is a remaining significant emission of gamma-rays. The emission is best modeled by a two dimensional Gaussian source with a width of 2° and a power-law energy spectrum (Equation 5.4). The energy spectrum has an Index of 2.175 and a Normalization of $6.846 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} \text{ sr}^{-1}$, at a Pivot energy of 1 GeV. The best fit model has a significance of 10σ over the background for energies above 1 GeV. In astrophysics usually a significance of over 5σ is required for a definite detection of a new source (Section 5.5). The best-fit spectral energy density that was found by the study is shown in Figure 3.4. Below 1 GeV the study was only able to determine upper limits for the spectrum.

Figure 3.3: Smoothed photon counts maps for 10-100 GeV. (A) Total emission. (B) All known sources, other than γ Cygni, subtracted. (C) γ Cygni subtracted. (Figure from [Ackermann et al., 2011])

Figure 3.4: Energy spectrum of the Cocoon emission found in [Ackermann et al., 2011] (Created with data from Table S1 from the supporting online material)

The cocoon gamma-ray signal is from a volume of freshly accelerated cosmic rays that likely originate from the Cygnus OB2 OB association. The SNR γ Cygni is also a possible source for the cosmic rays, however it is unlikely since the excess is to only one side of γ Cygni. It is thought that the Cocoon's gamma-ray signal is mainly due to π^0 decay from proton interactions. [Ackermann et al., 2011]

Chapter 4

Detection of Gamma rays

Figure 4.1: Atmospheric opacity to the electromagnetic spectrum depending on wavelength (credit: NASA)

As gamma-rays are photons with energies > 100 keV corresponding to wavelengths of less than 10^{-11} meters, then the atmosphere is completely opaque to them. This

means that space based detectors are the only method to directly observe gamma rays originating from space. However because of the high energies of gamma-rays when they interact with the atmosphere ground based observatories can be used to detect the air showers that result from their impacts with the atmosphere.

In this thesis uses the results from data obtained both with the FERMI-LAT instrument and HAWC observatory for analysis of the Cocoon. The combined analysis would allow for study of the Cocoon across the energy range of 1 GeV to 100 TeV.

Space Based

The first detection of gamma rays by a space based detector was between April and September of 1961, when Explorer XI detected 22 gamma rays. Explorer XI was equipped with a crystal scintillator, surrounded by an anti-coincidence shield. Explorer XI operated was able to detect gamma-rays with energies over 50 MeV, however the detector was not able to be pointed so it could only look in one direction.[Kraushaar and Clark, 1962]

The first all-sky gamma-ray survey was performed by the third Orbiting Space Observatory (OSO-3) between March 1967 to June 1968. OSO-3 was equipped with the a similar detector as Explorer XI and detected 621 gamma-rays. One of the primary

accomplishments of OSO-3 was to determine that gamma-rays origins are primarily in the galactic plane, notably the galactic center.[Clark et al., 1968]

The following gamma-ray space telescope, the second Small Astronomy Satellite (SAS-2 or SAS-B), was the first satellite whose primary mission was gamma-ray astronomy. The previous gamma-ray detectors had been secondary sensors. SAS-B was operated from November 1972 to June 1973 during which it detected 13,000 gamma-ray events between 20 MeV and 1 GeV. SAS-B made the first detections of gamma-ray point sources (the Crab and Vela pulsars). The sensor that SAS-B was equipped with was composed of a pair of spark chambers.[Derdeyn et al., 1972]

The first gamma-ray catalog was created using the European Space Agency's COS-B. COS-B operated between 1975 and 1983 and could detect gamma-rays between 30 MeV and 3 GeV. The catalog had 25 sources that were found with the 200,000 gamma-rays that COS-B detected. COS-B used a similar detector to SAS-B but also with a calorimeter to improve its energy measurement. [Bignami et al., 1974] One of the most recent gamma-ray space based gamma-ray satellite is the Fermi-LAT and is discussed in the following section.

FERMI-LAT

Overview

The Large Area Telescope (LAT) is a gamma-ray detector onboard the Fermi Space Telescope. The telescope was launched in 2008. The LAT was originally designed to be sensitive to gamma rays with energies between 10 MeV and 300 GeV [Atwood et al., 2009]. However after analysis improvements the energy range was extended to between 10 MeV and 2 TeV [Bruel, 2014]. The LAT has a large field of view of 2.4 steradians. The LAT covers the whole sky roughly every 3 hours[Atwood et al., 2009]. Its angular resolution is dependent on the energy of the gamma ray (3.5° at 100 MeV and less than 0.15° at energies above 10 GeV for the event type used in this analysis). Fermi-LAT has detected 3033 sources with a significance above 4σ between 0.1-300 GeV [Acero et al., 2015].

Operation

The LAT works by allowing gamma-rays through an Anticoincidence shield. The Anticoincidence shield is composed of plastic scintillators that detect when a charged particle (proton or electron) enters the LAT. This allows the rejection of 99.97% of

Figure 4.2: Fermi Satellite (credit: NASA/Sonoma State University/Aurore Simonnet)

cosmic rays that enter the detector [Moiseev et al., 2007].

The gamma-ray then passes through 16 sets of conversion foils and particle tracking layers. The Conversion foil, made of tungsten, allows for the gamma-rays to change into e^+e^- by pair production. The first twelve layers of tungsten are thin at 0.095 mm (FRONT) while the last four are thick at 0.72 mm (BACK). The FRONT has about two times better angular resolution compared to the BACK. The BACK increases the effective area at high energies and statistics at lower energies. [Atwood et al., 2007]

The origins of the gamma-rays are found by the particle tracking layers. There are 16 particle tracking layers[Atwood et al., 2009], this allows the detector to determine the source location of the gamma-ray with in 1° to 0.1° . The angular resolution is dependent on the energy of the gamma-ray and is shown in Figure 4.4.

The Calorimeter measures the energy of the e^+e^- pair to find the energy of the

incident photon, along with an additional ability of cosmic ray rejection. [Atwood et al., 2009] The structure of the LAT is shown in Figure 4.3.

Figure 4.3: Schematic structure of the LAT https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Introduction/LAT_overview.html

Figure 4.4: Fermi-LAT energy independent Point Spread Function (PSF) http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Ground Based

When high energy gamma-rays interact with the atmosphere they produce air showers through $e^\pm$ pair production and Bremsstrahlung radiation (Section 2.1.2). Pair production occurs when the gamma-ray passes near an atomic nucleus resulting in a photon converting into an electron-positron pair. The air-shower that this produces can be seen in figure 4.5.

There are two primary methods for observing gamma-ray air showers: Imaging Atmospheric Cherenkov Telescope (IACT) and Extended Air Shower (EAS) arrays.

Figure 4.5: Gamma-ray air shower (credit: Los Alamos National Labs) http://www.thelivingmoon.com/45jack_files/03files/HAWC_and_the_Future.html

As the air shower electrons/positrons pass through the atmosphere they are commonly traveling at faster than the speed of light in air ($0.99972c$). This causes them to emit Cherenkov radiation. As the opening angle of cherenkov radiation in air is less than 1° the IACT needs to be pointing at the gamma-rays source location, this is shown in Figure 4.6. This means that IACT arrays like VERITAS, sensitive to 100 GeV to more than 30 TeV, have high angular resolution (VERITAS: 68% containment radius of less than 0.1° at 1 TeV) but narrow fields of view (VERITAS: 3.5°) [Park et al., 2015]. Additionally due to the IACTs use of arrays of very sensitive photomultiplier

tubes to detect the faint cherenkov light, IACTs are not able to operate during the day or nights with too much moonlight or when there is bad weather. VERITAS for example can only make about 1,000 hours of observations during an eight month observing season (an uptime of $\sim 17\%$) [Holder et al., 2008]

Figure 4.6: Cherenkov light produced by a gamma-ray air shower (<http://www.isdc.unige.ch/cta/outreach/data>)

EAS arrays directly detect the particles of the air shower as they pass through a ground based detector. An EAS array is normally composed of hundreds of detectors spread over a large area. There are currently two types of EAS detectors being used Water Cherenkov Detectors, and Scintillators. EAS arrays are able to operate at all times as they require the particles to enter the detectors so they have an up time of $\sim 95\%$. EAS arrays have a lower angular resolution (HAWC: about 0.5° at 1TeV [Figure 4.11]), but a larger field of view(HAWC: about 81° [Abeysekara et al., 2014]) when compared to IACTs. EAS arrays also have an intrinsic lower limit of energy of

~ 10 GeV [Smith et al., 2007].

A Water Cherenkov Detectors detect the air shower particles when they pass through a water tank at higher speed than the speed of light in water ($0.7502c$). This causes the particles to release Cherenkov light, which is detected by photomultiplier tubes in the tank.

By determining the time each tank started detecting air shower particles, the angle of the air shower front can be determined. With the angle the air shower front the arrival direction of the primary particle can be determined. An example of a Water Cherenkov Detector is shown in Figure 4.7.

Scintillators detect an air shower when the particles or photons pass through the scintillator. The scintillator material fluoresces when it is hit by ionizing radiation. The attached photomultiplier tube amplifies the fluorescence light for the detection. The scintillator is composed of a high electron density material, such as plastic. An example of a scintillator detector is shown in Figure 4.8

Figure 4.7: A HWAC Water Cherenkov Detector (Credit: HAWC/WIPAC) <https://hawc.wipac.wisc.edu/gallery/view/1695>

Figure 4.8: A Scintillator detector composed of a scintillator attached to a photomultiplier tube (<https://web.stanford.edu/group/scintillators/scintillators.html>)

HAWC

The High Altitude Water Cherenkov (HAWC) observatory is ground based gamma-ray detector located on the Sierra Negra volcano in Mexico. The detector is located at an altitude of 4100m and was completed in 2015. The detector is sensitive to 1-100 TeV gamma rays and has a field of view of 2sr, the all-sky map that it produces can be seen Figure 3.1(b). The layout of HAWC can be seen in Figure 4.9, along with its location in Mexico.[Abeysekara et al., 2014]

HAWC is an array of 300 Water Cherenkov detectors (shown in Figure 4.7) that detect the particles of an air showers that are produced by high energy gamma-rays and cosmic rays. As shown in Figure 4.10 the number of particles in a shower is dependent on the amount of atmosphere the shower has passed through. When compared to its predecessor MILAGRO, Air showers will be about two times the size as seen by HAWC. This along with an changes in design has greatly improved HAWC's angular resolution over MILAGRO as seen in Figure 4.11.

Figure 4.9: (Credit: HAWC/WIPAC) <https://hawc.wipac.wisc.edu/gallery/view/1695>

Figure 4.10: The Air shower size is dependent on the atmospheric Depth
[Ayala Solares, 2017]

Figure 4.11: HAWC Angular resolution in 68% containment Point Spread Function (PSF) compared to MILAGRO <https://www.hawc-observatory.org/observatory/sensi.php>

Chapter 5

Data Analysis

For this thesis it was decided to perform a binned likelihood analysis of the *clean* data class for the study of the Cocoon. The reasons for these choices and the analysis processes that are used in this thesis is described in the following sections.

Fermi Science Tools

Fermi Science tools¹ are a set of publicly available programs² used for LAT pass 8 data analysis. Pass 8 data is the latest event-level analysis, which improves sensitivity and angular resolution, which allows for source analysis at higher energies than previously

¹Fermi Tools version v10r0p5 was used

²The programs may be found at <https://fermi.gsfc.nasa.gov/ssc/data/analysis>

possible [Atwood et al., 2013]. Fermi Science tools support both binned and unbinned analysis types. With the Cygnus Region being on the galactic plane and the use of multi-year data sets, there are large available gamma-ray statistics and the binned likelihood analysis method is chosen.

Event Classifications

There are four main classifications of showers used by LAT, referred to as events, for non-transient phenomenon, *source*, *clean*, *ultraclean*, and *ultracleanveto*. The classification depends on how well the shower was reconstructed and how likely the shower was a miss-classified cosmic ray. Source events is the data type is best for point sources and some extended sources. Clean data is similar to source data except above 3 GeV where it has only 25% -50% of the background. It is recommended for examination of sources at high galactic latitudes. Ultracleanveto data is the cleanest data type available as it has only 25% -50% of the background of source for >100 MeV, it is used for studies of diffuse emission that require low Cosmic Ray contamination. The Clean event class was used due to the primary objective of this study being analysis at above 1GeV.

Binned Likelihood Analysis

The likelihood analysis method is based on creating a model of sources and comparing it to the data. The model parameters are varied to maximize the likelihood (5.1). For Binned likelihood analyses, events are binned in spatial and energy bins to shorten the computational time.

From a list of events Fermi-LAT has observed from a region a base counts map of the area is created. A list of sources that are present in and sources that may extend into the region of interest is created; in this case by searching the 3FGL catalog for all sources in are present in the region [Acero et al., 2015]. For this analysis the region of interest used was 10° in radius and centered on $(RA = 305.3^\circ, DEC = 40.5^\circ)$, which is the modeled center of the Cocoon. Using a file of the telescope's active time, orbit, and the direction the LAT was pointing an expected exposure map for the area is created. The spectral parameters of significant sources near the Cocoon are fitted to the base data map, while small sources near the cocoon or sources far from the cocoon are fixed to the 3FGL Catalog values. The exposure map and the fitted spectral parameters are used to create a model map. Once the model map is finished it is subtracted from the base counts map to form a residual map of region. This residual map is used to find areas where the model does not explain what is observed. Possible reasons for the excesses could be incorrectly modeled sources or

also sources which were not modeled.

The maximum likelihood (L) is calculated by multiplying the probability (p_i) of the modeled number of counts in a spatial and energy bins resulting in the observed number of the counts in the bin.

$$L = \prod_{bins\ i} p_i \quad (5.1)$$

The probability of the observed number of counts per bin based on the modeled number of counts is given by poisson distribution (equation 5.2) where m_i is the number of counts modeled in the bin and n_i is the number of events observed in the bin.

$$p_i = m_i^{n_i} \frac{e^{-m_i}}{n_i!} \quad (5.2)$$

Equation 5.2 may be inserted into equation 5.1, then e^{-m_i} may be pulled out of the product resulting in $e^{-M_{exp}}$ where M_{exp} is the total number of events modeled. The parameter m_i is dependent on the model spectrum parameters.

$$L = e^{-M_{exp}} \prod_{i=1}^{all} \frac{m_i^{n_i}}{n_i!} \quad (5.3)$$

Spectral Analysis

For the Cocoon a powerlaw spectrum is used by the Fermi Collaboration, as it was the result found in [Ackermann et al., 2011]. Equation 5.4 is used for power law where E is energy, N_0 is the normalization, N is the number of emitted photons, γ is the spectral index, and E_0 is the pivot energy.

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\gamma} \quad (5.4)$$

For a powerlaw spectrum the error is found with equation 5.5, where N_{err} is there Normalization error, and γ_{err} is the spectral index error.

$$\Delta \frac{dN}{dE} = \frac{dN}{dE} \sqrt{\frac{N_{err}^2}{N_0^2} + \gamma_{err} \log^2 \left(\frac{E}{E_0} \right)} \quad (5.5)$$

For the analysis it was also attempted to fit the Cocoon with a LogParabola spectrum as there is an observable drop off in the spectral energy density (Section 7.1.3). The equation for LogParabola is equation 5.6 where E is Energy, N_0 is the Normalization, E_0 is the pivot energy, α and β are the parts of the spectral index.

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\left(\alpha + \beta \log \left(\frac{E}{E_0} \right) \right)} \quad (5.6)$$

For fitting a binned energy spectrum for the Cocoon, the data was split into 12 energy bins (Table A.1). For the full energy range spectral, the pivot energy of the Cocoon was fixed while the normalization and index were fitted for the powerlaw spectrum. For the LogParabola the normalization, α and β were fitted. For analysis of the individual energy bins only the normalization was fitted while the other parameters were set to the values found from the full energy range analysis.

Determining Source Significance

A likelihood ratio test is used to assess the statistical significance of a potential new source compared to the background fluctuations. The test statistic (TS) is defined in equation 5.7 where $L_{max,0}$ is the maximum likelihood without the source, and $L_{max,1}$ is the maximum likelihood with the point source.

$$TS = -2 \left[\ln(L_{max,0}) - \ln(L_{max,1}) \right] \quad (5.7)$$

According to Wilk's theorem, the square root of the TS is distributed according to a

gaussian with mean 0 and width of 1, so to convert TS to significance (σ) is Eqn. 5.8

$$\sigma = \sqrt{TS} \tag{5.8}$$

Commonly in astrophysics a $\Delta\text{TS}=25$ (corresponding to a significance of 5σ) is the threshold for a new source to be detected. Where 5σ corresponds to a 99.99999% confidence of detection over the background fluctuations.

Chapter 6

Reproduction of Previous Results

The analysis was begun by reproducing the results of the previous study [Ackermann et al., 2011]. The first two years of Fermi-LAT data (August 2008 to August 2010) were used to replicate the paper’s results. This was done to determine if changes to LAT data analysis methods had altered the shape or spectral energy density of the Cocoon.

Maps

The residual map in Figure 6.1 is created by fitting all sources other than the Cocoon to the region with the method described in Section 5.3 for the energy range of 10-100 GeV. An excess was found in the same location as in [Ackermann et al., 2011], additionally the shape of the Cocoon is consistent with that found in the paper. The overlay in used Figure 6.1 part B was made from the C map from Figure 3.3 and outlining at the 0.2 counts line.

Figure 6.1: Counts plots after subtracting all known sources other than the Cocoon for 0-2 years of data 10-100 GeV, map B has an outline of the Cocoon from [Ackermann et al., 2011] overlaid on the same map as map A. The overlay contour is black and represents 0.2 photon counts contour line from [Ackermann et al., 2011]. The maps were smoothed with a gaussian of 0.25 degrees radius. The scale of the maps is in residual photon counts per pixel.

Energy Spectrum

To model the energy spectrum for the Cocoon, the same Gaussian spatial model as in the 3FGL catalog is used [Acero et al., 2015]. This spatial model has a 68% containment radius of 3° and is centered at $RA = 305.3^\circ, DEC = 40.5^\circ$. The energy range of 1 GeV to 870 GeV was split into 8 logarithmically spaced energy bins (Table A.1). As can be seen in Figure 6.2, the energy spectrum found approximately matches up with the spectrum found in [Ackermann et al., 2011]. The best fit Powerlaw spectrum for 1-870 GeV was found, for this the index and normalization were fitted while the pivot energy was fixed to the 3FGL value of 1,000MeV. For 1-870 GeV the best fit values were found to be $N_0 = 7.10 \pm 0.56 \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ and $\gamma = 2.056 \pm 0.031$. With the fit a TS value of 400.7 corresponding to a significance of 20.2σ was found.

$$photons = (Area)(ToT)(Time)(EnergyRange) \frac{dN}{dE} \quad (6.1)$$

Using the binned energy spectrum LAT detected 541 photons from the Cocoon between 10 and 100 GeV (Table A.4). The number of photons was calculated for each energy bin (Table A.1) using equation 6.1. Where the Area is the effective area of the LAT in the energy range 0.8meters^2 . ToT is the present of the time LAT was

Figure 6.2: Spectral energy density of the Cocoon compared to the results found in [Ackermann et al., 2011] for the 2 year Cocoon energy spectrum (Figure 3.4).

viewing the Cocoon which was found to be 38.2%, since LAT has a field of view of 2.4 sr, and assuming the LAT had an equal time looking at every part of the sky $\frac{2.4}{4\pi} = 19.1\%$. Time is the time range of the data set in seconds, for the 2 year data set Time is 63,113,904 seconds. The Energy Range is the $(E_{max} - E_{min})$ for the energy bin.

In Figure 6.2 the previous results data is from [Ackermann et al., 2011]. The dashed line is from a single fit of the Cocoon for the energy range of 1-870 GeV. For this fit the normalization and spectral index were fitted, while the pivot energy was fixed. The shaded region around the dashed line is generated with equation 5.5 and represents the 1σ contours. The green points represent the spectral energy density of the Cocoon

in an energy range (Appendix A.1). For this fit the normalization was fit, while the pivot energy and index were fixed. The index was fixed to the value found in the 1-870 GeV fit. The error bars are generated with equation 5.5 and represent the 1σ error. The reason that there are two additional energy bins in this study at over 100 GeV is that the improved sensitivity of pass 8 data analysis (Section 5.1) allows for analysis at higher energies.

Chapter 7

Expanding on Analysis

8 Years of Data

With the results of the paper [Ackermann et al., 2011] reproduced the analysis was expanded to include the 6 additional years of data gathered by Fermi-LAT since 2011. With the improved event reconstruction mentioned in Section 5.1 analysis was expanded from a maximum energy of 100 GeV in [Ackermann et al., 2011] to 870 GeV.

Maps

The maps for the Cocoon with 8 years of data are shown in Figure 7.1. It can be seen that the spatial distribution had not changed significantly from 2 years to 8 years of data. Figure 7.2 and Figure 7.3 shows that the model with the Cocoon is equivalent to the photon counts map.

Figure 7.1: Residual plots after subtracting all known sources other than the Cocoon for 0-8 year 10-100 GeV, map B has an outline of the Cocoon from the paper overlaid on the same map as map A. The overlay contour is black and represents 0.2 counts contour line from [Ackermann et al., 2011]. The maps were smoothed with a gaussian of 0.25 degrees radius. The scale of the maps is in residual photon counts per pixel.

Figure 7.2: 8 Year Counts and Model maps for 10-100 GeV. Map A is the photon counts map of the Cocoon region. Map B is the model photon counts map of the Cocoon Region (including the Cocoon). The maps were smoothed with a gaussian of 0.25 degrees radius. The scale of the maps is in residual photon counts per pixel.

Figure 7.3: 8 Year Residual maps of the Cocoon region. Map A is the Residual photon counts map without the Cocoon subtracted, while Map B has the Cocoon subtracted. The maps were smoothed with a gaussian of 0.25 degrees radius. The scale of the maps is in residual photon counts per pixel.

Energy Spectrum

Figure 7.4 shows the spectral energy density for the Cocoon found with 8 years of LAT data. The spectrum derived from the 8 year dataset was found to be compatible with the 2 year dataset within uncertainties. For 1-870 GeV the fitted values were found to be $N_0 = 6.86 \pm 0.12 \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ and $\gamma = 2.072 \pm 0.017$ with a TS value of 1482 and a significance of 38.50σ . Figure 7.4 is setup in the same way as described in Section 6.2. Using the same method as found in Section 6.2, it was found that LAT has detected 1,771 photons from the cocoon in the energy range of 10 to 100 GeV (Table A.4).

Modeling the Cocoon as LogParabola

The full range Cocoon energy spectrum (1-870 GeV) lies outside of the error bars of the final two energy bins for the 8 year dataset (Figure 7.4). For energy bin 11 (100-271 GeV) the flux value observed is 4.4σ below the value predicted by the Powerlaw energy spectrum. For energy bin 12 (271-870 GeV) the flux value observed is 13.78σ below the value predicted by the powerlaw energy spectrum.

A possible explanation for the apparent fall off of the last energy bin of the binned energy spectrum is that the Cocoon does not follow a Powerlaw energy spectrum.

A Logparabola energy spectrum was fit to the Cocoon. For 1-870 GeV the fitted values were found to be $N_0 = 6.44 \pm 0.20 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$, $\alpha = 2.099 \pm 0.025$ and $\beta = 0.101 \pm 0.015$ while the pivot energy was fixed at 10 GeV. The spectrum is shown in Figure 7.5. A TS value of 1517 corresponding to a significance of 38.92σ were found. The difference in the TS between the Logparabola and Powerlaw spectrums for the Cocoon is $\Delta\text{TS}=35$. This means that the Logparabola spectrum is significantly preferred over the Powerlaw spectrum. Figure 7.5 is setup in the same way as described in Section 6.2. Usinsing the same method as found in Section 6.2, it was found that LAT has detected 1,198 photons from the cocoon in the energy range of 10 to 100 GeV (Table A.4).

Figure 7.4: Spectral energy density of the Cocoon with 8 years of data for energies between 1 and 870 GeV with energy spectrum from the paper overlay

Figure 7.5: Spectral energy density of the Cocoon with 8 years of data for energies between 1 and 870 GeV with energy spectrum of the LogParabola Cocoon model

Cocoon Variability

With four times the data it can be determined if the location or the spectral energy density of the Cocoon changes with time. As the Cocoon is not expected to be variable this is a good check to make certain the data and analysis methods are consistent.

Maps

The 8-year data set was evenly split into four evenly sized sets (Appendix:Table 2). It was found that the size, shape, and the location of the Cocoon did not vary over time. The maps are shown in Figure 7.6.

Energy Spectrum

Using the method that was used to find the spectrum for the first two years was repeated for the rest of the data. The resulting spectrums are shown in Table 7.1 and plotted in Figure 7.7. It was found that the Cocoon energy spectrum for each of the 2-year data sets agreed with the spectrum from the previous study [Ackermann et al., 2011].

It was found that neither the Cocoon's shape nor spectral energy density varies with over the time range used. This means that the Cocoon data and analysis methods are consistent.

Figure 7.6: 10-100 GeV Residual plots for 2 year segments of Fermi Data. The Time ranges for the maps are A is 0-2 years, B is 2-4 years, C is 4-6 years, D is 6-8 years. The maps were smoothed with a gaussian of 0.25 degrees radius. The scale of the maps is in residual photon counts.

Time Range	Normalization	Spectral Index	TS value	Significance (σ)
0-2 years	7.10 ± 0.56	2.056 ± 0.031	400.7	20.02
2-4 years	7.26 ± 0.56	2.133 ± 0.033	350.0	18.71
4-6 years	6.44 ± 0.55	2.095 ± 0.034	317.2	17.81
6-8 years	5.40 ± 0.46	1.977 ± 0.044	428.8	20.71
0-8 years	6.86 ± 0.12	2.072 ± 0.017	1482	38.50

Table 7.1

Spectrum found for the different time ranges for the energy range of 1-870 GeV. A fixed pivot energy of 1 GeV was used for all fits. The normalization has units of $10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$.

Figure 7.7: Spectral energy density for the Cocoon in the four time ranges.

Analysis Outside 1-870 GeV

Early in February 2017, the LAT collaboration released the preliminary version of the third high energy catalog (3FHL) which included sources from 10 GeV to 2 TeV.

With this expanded energy range it was attempted to extend the analysis to energies above 870 GeV. However it was found that there were not enough events at the higher energy ranges to perform a meaningful analysis of the Cocoon. Above 870 GeV there were found to be only 5 events for 0-2 years and 10 events for 8 years of data in the region of interest. Additionally it was found that for energies below 1 GeV, systematic uncertainties in the data caused by the diffuse emission make it difficult to do meaningful analysis on large diffuse objects. These systematic uncertainties are related to the treatment of the diffuse emission in the region.

HAWC Sensitivity to the Cocoon

If a combined analysis can be done with Fermi-LAT and HAWC data, it would allow for a spectral analysis from 1 GeV to 100 TeV. An analysis across the larger energy range would allow for an improved fit for the spectral energy of the Cocoon.

HAWC's sensitivity to an object depends on the celestial declination (along with spectral shape, extension, cutoff....) of the object. The Cocoon is located at a declination of 40° , so according to Figure 7.8 the Cocoon needs a flux of at least $5 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$ above 2TeV with 1 year of HAWC data. The Cocoon (Powerlaw, with 8 years of data) would have an integral flux above 2TeV of $3.717 \times 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$, so the Cocoon should be visible to HAWC if it has a PowerLaw spectrum. However if

the Cocoon has a logparabola spectrum, it would have an integral flux above 2TeV of $1.044 \times 10^{-18} \text{ cm}^{-2}\text{s}^{-1}$, so the Cocoon would not be visible to HAWC. The Cocoon is smaller than the 5° degrees radius source used in Figure 7.8, at 3° radius so it will require a lower minimum flux to be detected by HAWC.

Figure 7.8: HAWC's sensitivity to 5 degree radius diffuse sources with different time spans of data [Ayala Solares, 2017]. The Flux of the LAT Cocoon powerlaw (PL) and logparabola (LP) were marked, these data points were found by extrapolating the LAT spectrum to HAWC energy ranges.

Possible HAWC Detection of The Cocoon and Combined Energy Spectrum

For the HAWC analysis of the Cocoon, 27 months of HAWC data was used. The current model for HAWC data in the Cygnus region resulted in a Cocoon energy spectrum that is compatible with that obtained with Fermi-LAT data. In the Cocoon region HAWC detects the gamma-ray sources 2HWC J2031+415 and 2HWC J2020+403 [Abeysekara et al., 2017]. The source 2HWC J2020+403 is co-located with γ Cygni, while the 2HWC J2031+415 is at the location of the Cocoon and the pulsar wind nebula TeV J2032+4130. Figure 7.9 shows HAWC's view of the Cocoon region without any sources subtracted.

To determine the spectrum of the Cocoon with HAWC data, the three sources are modeled. γ Cygni is modeled as a point source with a powerlaw spectrum, with the Normalization and Index fitted while the Pivot energy was fixed at 7 TeV. An asymmetric Gaussian with a powerlaw spectrum with the parameters measured by VERITAS was fixed at the location of TeV J2032+4130. Figure 7.10 was obtained after subtracting these two sources, there is significant residual TeV photon emission overlapping the Fermi-LAT cocoon location. This emission is probably associated with the Fermi-LAT Cocoon at GeV energies.

The possible TeV counterpart of the Cocoon was modeled at the location of the Fermi-LAT cocoon and was modeled as a 2D Gaussian with a fixed width of 2° . A powerlaw energy spectrum with a fixed pivot energy of 7 TeV, while the normalization and spectral index were fitted. The spectrum for the possible TeV counterpart of the Cocoon was found to be $N_0 = 3.01 \pm 0.20 \times 10^{-19} \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ and $\gamma = 2.520 \pm 0.04$ with $E_0 = 7 \text{ TeV}$. [Hona et al., 2017]

In Figure 7.11 the 8 year Cocoon data found in Section 7.1.2 and Section 7.2.2 are compared to the HAWC cocoon spectrum. For the Fermi-LAT Powerlaw, the spectrum meet at 1 TeV, however the HAWC source has a softer spectrum. This could be the result of there being a break in the spectrum. For the Fermi-LAT Logparabola, the HAWC spectrum is about 10 times higher at 1 TeV than the LAT Logparabola spectrum. This could be the result of source confusion on with HAWC or the Fermi-LAT fit may not be accurate at above 100 GeV.

Figure 7.9: HAWC significance map of the Cocoon region with 27 months of data. [Hona, 2018].

Figure 7.10: HAWC significance map of the Cocoon region with the sources 2HWC J2031+415 and 2HWC J2020+403 subtracted. The contours are the 0.5, 0.7 and 0.9 photons per bin from Figure 7.3 map A [Hona, 2018].

Figure 7.11: HAWC measurement of the Cocoon spectral energy density compared to the 8 year LAT spectral energy density. The HAWC Cocoon spectrum was modeled from 1 to 100 TeV

Chapter 8

Conclusions

This study was able to replicate and expand upon the research done in the Paper: “A Cocoon of freshly accelerated cosmic rays detected by Fermi in the Cygnus superbubble” from 2011 [Ackermann et al., 2011]. The changes in LAT event reconstruction have not have altered the Cocoon’s location or energy spectrum. The location and energy spectrum of the Cocoon was found to be constant over time. Using Fermi-LAT data an analysis was not possible above 870 GeV due to limitations of data gathered by Fermi-LAT. In Fermi-LAT energy ranges 1-870 GeV the Cocoon is better modeled by a Logparabola than by a Powerlaw energy spectrum. The logparabala spectrum fit was strongly preferred compared to the powerlaw spectrum fit for the 8 year analysis.

The feasibility of analysis of the Cocoon with HAWC data was determined for both

spectrums found with LAT data. If the Cocoon has a powerlaw energy spectrum, there would be sufficient flux above 2 TeV for HAWC to detect it. If the Cocoon possess a logparabola energy spectrum however, there would not be sufficient flux above 2 TeV if to be detected in HAWC data. Analysis then was done comparing the found powerlaw and logparabola spectrum with a powerlaw source found with HAWC data [Hona et al., 2017] that is thought to be the Cocoon. It is found that the LAT powerlaw energy spectrum is equal to the HAWC powerlaw energy spectrum at 1 TeV, through the HAWC spectrum is softer. While the LAT logparabola energy spectrum is an order of magnitude lower at 1 TeV compared to the found HAWC energy spectrum.

If the HAWC source is the Cocoon there are several implications for the Cocoon. It would be evidence that there are protons in the Cocoon that are capable of producing gamma rays with energies upto 100 TeV. Additionally, while the logparabala spectrum is strongly preferred to the powerlaw spectrum in LAT energies (1-870 GeV), the powerlaw spectrum is the one that works for the combined analysis. Though there may be a break in the Powerlaw around 1 TeV that results in a softer spectrum above 1 TeV than below 1 TeV.

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Appendix A

Supplemental Data

Bin (#)	E _{min} (GeV)	E _{max} (GeV)
1	0.1000	0.1822
2	0.1822	0.3321
3	0.3321	0.6052
4	0.6052	1.0000
5	1.0000	1.8224
6	1.8224	3.3211
7	3.3211	6.0525
8	6.0525	10.000
9	10.000	33.210
10	33.210	100.00
11	100.00	271.90
12	271.90	870.00

Table A.1

Energy Ranges used for the spectrum analysis

Time Range	Start Time(Gregorian)	End Time(Gregorian)	Start Time(MET)	End Time(MET)
0-2 years	2008-08-04 15:43:36	2010-08-04 15:43:36	239557417	302629418
2-4 years	2010-08-04 15:43:36	2012-08-04 15:43:36	302629418	365787819
4-6 years	2012-08-04 15:43:36	2014-08-04 15:43:36	365787819	428859819
6-8 years	2014-08-04 15:43:36	2016-08-04 15:43:36	428859819	492018220
0-8 years	2008-08-04 15:43:36	2016-08-04 15:43:36	239557417	492018220

Table A.2
Time ranges for data analysis given in Gregorian and Mission Elapsed
Time (MET)

Bin (#)	0-2 years	2-4 years	4-6 years	6-8 years	0-8 years (PL)	0-8 years (LP)
1	9.15±0.82	7.43±0.80	6.79±0.81	6.54±0.75	7.48±0.34	6.52±0.41
2	5.37±0.63	4.08±0.62	4.31±0.55	4.73±0.57	4.80±0.27	3.94±0.29
3	5.37±0.65	4.31±0.66	1.97±0.64	1.80±0.59	3.58±0.29	2.70±0.32
4	4.59±0.70	3.29±0.72	2.42±0.69	2.07±0.59	3.30±0.32	2.76±0.34
5	5.12±0.75	4.86±0.72	3.92±0.66	2.08±0.63	4.44±0.36	3.87±0.32
6	5.13±0.60	5.18±0.63	6.22±0.66	3.68±0.60	5.61±0.31	5.08±0.33
7	6.53±0.86	5.61±0.75	4.24±0.83	4.50±0.61	5.50±0.42	4.70±0.39
8	3.85±0.98	3.33±0.92	1.67±0.95	NA±NA	3.93±0.45	2.95±0.48
9	8.49±1.22	5.23±1.18	4.46±0.93	6.13±1.07	7.21±0.55	4.60±0.57
10	6.22±0.02	1.63±1.40	3.22±0.39	4.33±1.28	4.31±0.65	3.69±0.68
11	5.00±1.76	4.12±0.03	3.54±0.35	4.27±0.35	2.99±0.35	2.87±0.70
12	1.95±1.85	2.54±0.28	2.01±0.28	0.004±0.024	0.745±0.29	0.348±1.65

Table A.3

Found flux values for each energy bin, all are in the form of $\times 10^{-5} \text{MeVs}^{-1} \text{cm}^{-2}$. PL is the PowerLaw spectrum for 0-8 years, LP is the LogParabola spectrum.

Bin (#)	0-2 years	2-4 years	4-6 years	6-8 years	0-8 years (PL)	0-8 years (LP)
5	2,401	2,277	1,838	1,725	8,328	7,254
6	1,524	1,589	1,812	1,343	6,792	6,133
7	975	1,675	1,267	1,288	6,566	5,606
8	282	488	245	NA	2,308	1,734
9	430	531	452	622	1,463	934
10	111	29	58	78	308	264
11	26	0	18	24	61	59
12	4	5	4	1	6	3

Table A.4

Photon flux values for each energy bin. PL is the PowerLaw spectrum for 0-8 years, LP is the LogParabola spectrum.

Appendix B

Sources Near the Cocoon

3FGL Catalog Name	Other Names	Source Type
0°-1° from Cocoon center		
J2028.5+4040c		
J2032.2+4126	TeV J2032+4130	PWN
J2032.5+4032		
1°-2° from Cocoon center		
J2032.5+3921		
J2037.4+4132c		
J2021.0+4031e	Gamma Cygni	SNR
J2021.5+4026		Pulsar
J2023.5+4126		
J2026.8+4003		
2°-3° from Cocoon center		
J2018.6+4213		
J2022.2+3840		SNR/PWN
J2033.3+4348c		
J2034.4+3833c		
J2034.6+4302		
J2036.8+4234c		
J2038.4+4212		
J2039.4+4111		
J2042.4+4209		
3°-4° from Cocoon center		
J2011.1+4203		
J2018.5+3851	TXS 2016+386	Blazar
J2024.6+3747		
J2030.8+4416		Pulsar
J2043.1+4350		
4°-5° from Cocoon center		
J2015.6+3709	MG2 J201534+3710	Blazar (FSRQ)
J2021.1+3651		Pulsar
J2030.0+3642		Pulsar
J2035.0+3634		

Table B.1

The type and other names for the 3FGL Gamma-Ray Sources within 5° of the center of the Cocoon, if available.