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Phase Resolved Analysis of Pulsar PSR J2032.2+4126

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PHASE RESOLVED ANALYSIS OF PULSAR PSR J2032.2+4126

By

Aishwarya Satyawar Dahiwal

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Physics

MICHIGAN TECHNOLOGICAL UNIVERSITY

2020

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

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Preface

The data used for analysis in this report is obtained from the publicly available database¹ of Fermi-LAT. The python package, Fermipy¹ was used which facilitates the analysis of data obtained from Fermi-LAT along with the publicly available NASA software package "Fermi Science Tools" or "Fermi Tools"² version v11r5p3.

Data selected was in the energy range from 1 GeV to 500 GeV over a period of ten years starting from 2008-08-04 to 2018-08-04. The region of interest was selected to be 15° centered at the location of PSR J2032.2+4126 with RA = 307.17° , Dec = 41.17° . Pass 8¹⁴ data with event class "Source" was used. The Galactic Diffuse Emission model used is gll_iem_v06.fits²⁹ and the isotropic diffuse model selected is iso_P8R2_SOURCE_V6_v06.txt

¹<https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>

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I would also like to thank my friends for all of their support and without whom this wouldn't have been half as fun as it was. I would like to thank Vineet Rodrigues for being the backbone throughout the past few years, Omkar Bhumkar for his constant encouragement, support and patience, Sambhawana Sharma and Oindabi Mukherjee for being my home away from home, Kusuma Pallapotu and Aditya Basina for the amazing meals and conversations that made coming back home exciting.

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Abstract

Pulsars are an extremely dense and highly magnetized rotating neutron stars. Their periodic rotation produces pulsed emissions and this periodicity makes them a very useful tool in various studies. Hundreds of γ -ray pulsars have been discovered with the increasing number of telescopes and observing facilities. The Fermi Large Area Telescope (LAT) has been taking data from the direction of the Cygnus region and has reported multiple pulsars in the region. One of the brightest pulsars reported is PSR J2032.2+4126, which has been detected at both radio and gamma ray energies. Emission from these bright pulsars outshine the gamma ray sources in their vicinity. Hence, in addition to understanding the pulsar, estimating the on-pulse and off-pulse periods of the pulsar can be crucial to understand and analyze the fainter sources in the nearby region. PSR J2032.2+4126 lies directly on top of the Cygnus cocoon, thus this analysis will be used to understand the background in the extended emission analysis from the cocoon region.

Chapter 1

Introduction

Pulsars are extremely dense and highly magnetized rotating neutron stars whose beams of radiation are pointed towards us. Pulsars have been found to emit in radio waves, visible light, x-rays and γ -rays. There also exist neutron stars whose beams of radiation never reaches Earth as it is not directed towards us. The periodic rotation of a neutron star produces pulsed emissions when these beams sweep across the Earth and this periodicity makes it a very useful tool in various studies.

With the increase in the number of telescopes and ground based observatories, the study of VHE(Very-High Energy) gamma-ray astronomy, where the photon energies range from 10^{11} eV, up to about 10^{14} eV, has certainly gained momentum. All of these facilities provide data which can help open new windows to test fundamental

physics by trying to answer questions such as the origin and acceleration of cosmic rays and the existence and distribution of dark matter.

Whether it is a supernova remnant we are trying to explore or any other region of the sky that needs to be carefully observed, if a bright pulsar lies in the region of interest, it outshines other gamma ray sources in its vicinity. The strong emission coupled with the short duration of rotation makes the situation even more complicated as these pulses occur every few seconds or in some cases milliseconds, dominating the data collected from that region. Hence, in addition to understanding the pulsar, estimating the on-pulse and off-pulse periods of the pulsar can be crucial in removing the on-pulse events so as to minimize the signal from the pulsar when studying other nearby sources.

Several gamma ray pulsars have been observed in the Star Forming Region of Cygnus constellation of our Galaxy by various observatories such as VERITAS, Fermi-LAT, and HAWC. Table A.1 lists gamma ray pulsars in the Cygnus region found in the VERITAS survey of the region. The Cygnus constellation is of importance for several reasons. It is one of the brightest regions in the sky in all wavelengths¹³. It is also the host to various sources such as active star forming regions, supernova remnants and Pulsar Wind Nebula¹³. The Fermi Large Area Telescope (LAT) operates in an all-sky survey mode where the entire sky is imaged every two orbits which is approximately every 3 hours. The Cygnus region has also been observed as a part of this survey.

Fermi-LAT has reported multiple pulsars in the Cygnus region. One of the brightest pulsars reported is PSR J2032.2+4126, which has been detected at both radio and gamma ray energies. This Pulsar lies on top of the "Cygnus Cocoon" which is an extended source of gamma ray emission³⁰. This cocoon of freshly accelerated cosmic rays²⁰ are believed to have originated from the OB association Cygnus OB2³⁰. The study of the cocoon will thus help understand the acceleration of cosmic rays in star forming regions like Cygnus OB2.

There are three very bright pulsars that lie on top of the Cygnus cocoon, J2021+3651, J2021+4026 and J2032.2+4126⁷. The pulsating beams from these pulsars dominate the data collected from this region. This interferes with the analysis of the cocoon, which is where Pulsar gating analysis is helpful. To help minimize the effect of pulsars on their surroundings, in this report, a pulsar gating or a "Phase-resolved" analysis is performed on PSR J2032.2+4126. The analysis was performed using 10 years of Fermi data using publicly available Fermi Science tools and FERMIPY software¹. The report is organised as follows. Chapter 2 provides an introduction to gamma-ray astrophysics, various gamma-ray sources and Pulsars. In Chapter 3, the various observation techniques for gamma rays are discussed along with an explanation of the construction and working of Fermi-LAT. Chapter 4 and 5 talk about the analysis methods used in the project. This includes a detailed description of all the tools used, the data selection and the timing analysis performed. Chapter 6, which is the last chapter, summarizes the results and conclusions of the report.

Chapter 2

Introduction to Gamma-Ray Astrophysics

2.1 Gamma Rays

Gamma rays are high energy photons and messengers of electromagnetic radiation. These photons have the highest energy in the electromagnetic radiation spectrum and the shortest wavelengths. Gamma rays are produced by the interaction of cosmic rays, which are charged particles, with the interstellar medium or magnetic fields. The energy of gamma ray photons ranges from 100 KeV to ≥ 100 TeV¹⁵. Gamma rays travel in a straight line and thus trace back to the sites of acceleration

and propagation of cosmic rays. This also help with the understanding of the spatial distribution and energy distribution of such charged particles in our Universe.

Figure 2.1: The gamma ray sky : This is the all-sky map of the gamma rays detected by FERMI LAT at energies greater than 1 GeV based on five years of data collected. The color changes with the brightness of the gamma ray sources. Brighter colors indicate brighter sources(Credits: NASA/-DOE/Fermi LAT Collaboration)

2.2 Gamma-Ray Sources

Gamma rays are produced by some of the most energetic sources in the universe. Some of these sources are Pulsars¹⁶, Stars¹⁶, Supernovae explosions¹⁷, Pulsar Wind Nebulae¹⁸ and accretion disks around black holes¹⁶. Gamma

ray astronomy provides an opportunity to study these exotic objects.

2.2.1 Pulsars

Figure 2.2: Pulsar: A schematic diagram of Pulsar showing the beams of radiation which give rise to pulses of emission as the neutron star rotates. (credit: Handbook of Pulsar Astronomy¹⁹)

Pulsars are rapidly rotating neutron stars whose beams of radiation are directed towards Earth. Neutron stars are formed after the death of massive stars that have used up all of their fuel and collapse in on themselves. These are the remnants after huge explosions called Supernovas. The most common method of observing and identifying a neutron star is via their pulsed emission. There also exist neutron stars whose beams do not reach earth.

Pulsars are highly magnetized and have a really high spin speed ranging from 0.25 seconds to 2 seconds²⁷. Some pulsars also have a time period of 1 to 10 milliseconds, these are called millisecond pulsars²⁷. The blinking nature or the pulses of a pulsar are associated to the jets shooting out of the two ends as can be seen in Figure 2.2. As the pulsar spins these jets change their direction with respect to earth and hence we see change in intensity or the pulses. These pulses allow us to measure the period or the rate of spinning of a pulsar. They have the ability to radiate in multiple wavelengths, from radio to gamma rays¹³.

With the launch of Fermi LAT the number of gamma ray pulsars detected has increased significantly by a factor of 100. With the increase in this number, it is possible to perform population study of pulsars and also study the temporal as well as spectral features of pulsars in more detail. Fermi has shed light upon many characteristics of Pulsars as we know them today. Pulsars have energy-dependent light curves which usually exhibit a double peaked morphology and the pulse shape changes with the change in energy domain⁴². The radio pulse could be leading, aligned with or trailing the gamma ray pulse in phase⁴². There exists an inverse trend between the gamma ray peak separation and the radio to gamma phase lag⁹. High energy pulsars possess larger spin-down power($\dot{E}_{rot}$) which is the most energetic subpopulation of pulsars in terms of $\dot{E}_{rot}$ with a possible empirical limit at $\dot{E}_{rot} = 10^{33}$ ergs/s below which no pulsar has been yet detected. This "line of death" is based upon the older population of millisecond pulsars discovered so far.

With the increase in the age of pulsars, they become more efficient gamma ray emitters because they convert a larger fraction of their spin-down power to luminosity even if their spin-down rate is reduced. Their spectra exhibit a cutoff at around a few GeV^{9, 42}. This may be explained by the fact that the accelerating electric field ($E_{||}$) scales with magnetic field B_{LC} in outer-magnetospheric models and in the case of curvature radiation (CR) reaction where the acceleration rate balances this radiative loss rate, one expects $E_{cut} \propto E_{||}^{3/4}$ ^{9, 42}. Fermi observed that most of the pulsars in the second Fermi Pulsar Catalog⁹ favor a simple exponential cutoff while some require a sub-exponential cutoff but none required a super-exponential cutoff. It is also observed that most of the young pulsars occur near the galactic plane whereas the millisecond pulsar occur at all latitudes^{9, 42}. Photon spectral index softens with a higher value of $\dot{E}_{rot}$, this possibly results from the increase in pair production or onset of synchrotron radiation in energetic pulsars.

PSR J2032.2+4126 was first discovered by Fermi LAT in 2009^{36 42} in a blind search of Fermi LAT's gamma-ray data and was later detected in radio observations by Green Bank Telescope (GBT)⁴⁰. It is almost 1.4 - 1.7 kpc away⁴⁰ and has a period of 143ms³⁷. It has been observed at both radio and gamma ray energies³⁷. It has a spin-down power $L_{sd} = 1.7 \times 10^{38}$ erg/s and a characteristic age of $\tau = 180$ kyr^{38, 42}. It was considered to be an isolated pulsar⁴⁰ due to lack of apparent variation in the rotation caused by orbital motion. It was recently discovered that it is in a binary system with Be-star MT91 213. The observations of this pulsar revealed a dramatic change in the

spin-down rate which is attributed to the doppler effect due to the orbital motion of the pulsar in a long-period binary system with MT91 213^{38, 42}. They are in a highly eccentric orbit with a binary period of 50 years. This is second known TeV gamma ray binary system with a pulsar as the compact object. Periastron for this system occurred on November 13, 2017⁴¹. The x-ray flux and γ -ray flux both had a sudden increase before the Periastron and experienced a dip at the modeled location. However, there were some characteristic features which cannot be yet explained such as the sudden increase in the x-ray flux immediately after Periastron and the sharp dip in γ -ray flux after Periastron. There was no correlation between the time-dependent x-ray and VHE emission as was predicted. These are explained in detail in the paper "X-ray and TeV gamma-ray emission from the 50-year period binary system PSR J2032+4127/MT91 213"⁴¹.

Chapter 3

Observation Techniques

Gamma rays have the highest energies and the shortest wavelength in the electromagnetic spectrum. They span over seven decades in energy and thus a single type of instrument or technique cannot cover the entire range of energy⁵. The photon flux is also not consistent over the entire range of energy and drops rapidly as a function of energy. Thus, instruments with large detection area are desired to cover most of the energy range. At higher energies, gamma rays are blocked by the atmosphere before they reach the ground. This makes it important to have space-based observatories for the direct detection of these rays. These rays pass directly through the mirrors of the optical telescopes making it difficult to observe. The direct detection of gamma rays on ground is also extremely difficult as most of the gamma rays entering Earth's

atmosphere get absorbed and are blocked by the atmosphere. There are ways to detect gamma rays on the Earth's surface. Most of these detection techniques are based on the principle of detecting the secondary products of the interaction of gamma rays with the atmosphere. The ground based detection of gamma rays ranges from 100 MeV to 100 TeV. TeV gamma rays are the highest energy photons ever observed. Some of the observatories use the Cherenkov radiation that is produced by the secondary charged particles of the air shower produced by the interaction of gamma rays with the atmosphere. These air showers of the secondary charged particles have a trajectory such that the size of the shower increases up to a certain point above sea level, after which it starts to decrease again. Thus, observatories based on these air showers need to be located a particular distance above sea level. Also, the ground based observatories explore a higher energy range from 10s of GeV to 10s of TeV. Whereas, space-based telescopes probe the energy from KeV to GeV, with Fermi ranging upto 2 TeV²⁵. Thus there is a need for both ground based observatories and space based observatories to explore different energy ranges efficiently.

3.1 Space Based Observatories

One of the ways to detect gamma rays is by observing them before they enter the Earth's atmosphere, that is, in space. The first gamma ray telescope was launched

in the year 1961 aboard the American satellite Explorer 11¹. There are various instruments that are specifically designed to detect gamma rays in different energy ranges. In the year 2008, one of the most sensitive satellites was launched, the Fermi Gamma-Ray Space Telescope.

3.2 Fermi-LAT

The Large Area Telescope (Fermi-LAT), is the principal scientific instrument on-board the Fermi Gamma-Ray Space Telescope. It covers the energy range from $\simeq 20$ MeV to more than 1 TeV²⁵. The LAT's field of view covers approximately 20% of the sky at any time. Angular resolution (point-spread function, PSF, 68% containment radius) is 5° at 100 MeV, improving to 0.8° at 1 GeV, varying with energy approximately as $E^{-0.8}$ and asymptoting at 0.1° above 20 GeV²⁶.

3.2.1 Construction and Working of Fermi-LAT

The LAT has four main subsystems:

† The Tracker

¹<https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/explorer11.html>

† The Calorimeter

† The Anticoincidence Detector(ACD)

† The Data Acquisition System(DAQ)

Figure 3.1: Fermi-LAT - Structure²⁷

Figure 3.2: Fermi-LAT - Schematic structure²⁷

The LAT is a pair conversion detector. It has 16 tracker modules, each tracker is made of tower modules which consist of silicon-strip tracking detectors for charged particle detection along with thin tungsten converter foils⁸. The incident gamma rays interact with tungsten in the trackers to produce an electron-positron pair. The silicon strips in the tracker help trace the path of the pair produced to determine the direction of the entering gamma ray and also to reject the background. Since the rest mass of the electron and positron is much smaller than the gamma-ray energy of interest, the pair continues predominantly in the direction of the incident gamma ray, this helps reconstruct the events and give the energy and incident direction of gamma rays²⁵.

The pair then enters the calorimeter present at the bottom. The calorimeter consists of cesium iodide crystals. Each calorimeter module contains 96 cesium iodide crystals which are arranged in eight alternating orthogonal layers. They measure the energy of the particle in the LAT energy band. The cesium iodide present in the calorimeter produces flashes of light and the intensity of these flashes is proportional to the energy of the incoming particle. The total energy deposited by the particle is measured. The crystals are then read out by dual PIN photodiodes at each end^{25,8}. Since the pattern of energy deposition is different for both gamma rays and cosmic rays, the calorimeter also helps reject the background²⁵.

The ACD consists of 89 plastic scintillator tiles, which are read out by two photomultiplier tubes (PMT). The tiles are overlapped in one direction for maximum efficiency. The rate of cosmic-ray particles incident is much larger than the incoming gamma rays, roughly by a factor of 100,000 to a million. Thus there is an overwhelming background that has to be rejected for accurate measurement of the gamma rays. The scintillator tiles produce flashes of light when hit by the electrically charged cosmic rays, whereas the gamma rays being electrically neutral, are not affected by this. Thus this acts as a very important layer for the rejection of cosmic rays. This is possible because gamma rays are electrically neutral, and thus do not produce any signals or flashes in the ACD. The ACD rejects 99.97% of unwanted signals produced by cosmic rays. Along with the cosmic rays, neutrons could also have contributed to the background contamination. Although, free neutrons have a short life span and can only travel a distance of few parsec(pc) before they decay. "The decay time of a neutron with Lorentz factor γ is $t_n \sim 10^3 \gamma \text{ s}$ "⁴³; thus, after escaping, neutrons can travel to radii($R_n(\gamma)$) given by eqn 3.1 below.

$$R_n(\gamma) \simeq t_n * c \simeq 10^5 * \gamma \quad (3.1)$$

where R_n is the distance the neutrons travel, γ is the Lorentz factor, c is the speed of light, and t_n is the decay time for the neutrons. R is obtained in pc, and is dependent on the Lorentz factor that differs for different objects. Neutrons from the closest

supernova remnants need to have PeV energies or above for them to reach us, and neutrons from the Galaxy center will need to have ultra high energy for the same²⁸. The sources we look at are far less energetic and even further away. The neutrons would decay long before they reach us. Thus neutrons are not a concern as possible background for gamma ray detection.

The DAQ collects the information from location which is favorable to build a huge observatory at a specified distance above sea level is difficult.all the subsystems and performs on-board filtering and distinguishes between the cosmic rays and gamma rays to reduce the rate of background events that will be relayed to the ground. It also rejects events based on their arrival direction, thus rejecting gamma rays that originate in Earth's atmosphere.

Chapter 4

Analysis

Binned likelihood analysis is favored for most type of LAT analysis⁵ and was used in the analysis carried out for this project. The following sections describe in detail all the steps involved and the tools and software used in this analysis.

4.1 Fermi Tools

Fermi Tools or Fermi Science Tools², is a set of publicly available data analysis software. They are used for the analysis of data collected by both Large Area Telescope and the Gamma-ray Burst Monitor. Fermipy²⁴, which is a python package, is used along with Fermi Science Tools for analysis purposes. This package is built on the

pyLikelihood interface of Fermi tools. These together help with different aspects of analysis such as data and model preparation, generating the Spectral energy distributions of sources, their residual maps, counts maps, timing analysis and light curves. They can be used for both binned and unbinned analysis. Version v11r5p3 of Fermi Tools was used for this analysis.

4.2 Maximum Likelihood Analysis

Likelihood is the probability that the observed data will be obtained for a given input model. This input model for Fermi LAT is the distribution of gamma-ray sources in the sky which includes their intensity and spectra. It is calculated by multiplying the probability (p_i) of observing the detected number of events in each bin³⁰.

$$L = \prod_{bins_i} p_i \quad (4.1)$$

Here L is the likelihood and (p_i) is the probability. This probability (p_i) is given by a Poisson distribution shown in equation 4.2 below.

$$p_i = \theta_i^{n_i} \frac{e^{-\theta_i}}{(n_i)!} \quad (4.2)$$

Likelihood ratio test is used to determine the ratio of the likelihood of model over the background. It is given by

$$TS = -2\ln \frac{L_0}{L_1} \quad (4.3)$$

Here L_0 is the likelihood of the background, L_1 is the likelihood of the Model(source and background) and TS is Test Statistics. This TS is then used to calculate the significance(σ) which is given by

$$\sigma = \sqrt{TS} \quad (4.4)$$

A threshold of 5σ is used to establish the detection of gamma ray emission.

4.3 Data Selection and Configuration

Fermi-LAT records individual events and generates the reconstructed energy and direction of the incoming photon. These events are then classified into five categories namely Source, Clean, Ultraclean, Ultracleanveto and Sourceveto. These events are

stored in the LAT events files, and the position of the satellite is specified in the spacecraft files. The position and orientation information for the spacecraft is provided at 30-second intervals in the spacecraft file. The most current version of data available was selected, with the tightest background rejection criteria, the Pass 8 "Source" event class^{14,21}. Pass 8 has a narrower PSF compared to Pass 7 P7REP²² at higher energies and is better for source detection and localization. The Instrument Response Functions(IRFs) P8R2_SOURCE_V6 was used with a zenith angle of 90° . The event type was selected as "3" which includes front and back events, that is the events that are converted both in the front and back section of the tracker. The region of interest selected was 15° around the center located at PSR J2032.2+4126. The location of the pulsar PSR J2032.2+4126 is $RA = 307.17^\circ$, $Dec = 41.17^\circ$. The energy range selected was from 1 GeV to 500 GeV with the time period of 10 years starting from 2008-08-04 to 2019-03-04. The Galactic Diffuse Emission model used is `gll_iem_v06.fits` and the isotropic diffuse model selected is `iso_P8R2_SOURCE_V6_v06.txt`

Based on the data and the selected background models, the first step is to create a configuration file which includes the analysis parameters, like the data files, both event and spacecraft files, energy range, the start and end times for which the data is selected, binning, event class to be used and event type to be used for the analysis. The data section in the configuration file includes the input data set and spacecraft file for the analysis. The binning section defines the dimensions of the Region Of Interest(ROI) and the spatial and energy bin size. The selection section defines the

energy range, maximum zenith angle cut (z_{max}), event class and type and the time period. The model section defines parameters related to the ROI model definition such as diffuse templates used and catalogs. This file can also be used to customize many other parameters that can be useful for the analysis.

4.4 Methodology

The binned likelihood analysis begins with data preparation and response calculation needed for the analysis. The optimize step then loops over all the model parameters and performs a fit to obtain the normalization and spectral parameters for all the sources. This provides us with the TS of all the sources which helps in identifying the weak sources which were not significantly detected. All the sources below TS of 5 were removed from the further analysis.

I then freed the normalization for all the sources within 5° ROI, the isotropic diffuse component and all the parameter for the sources with TS higher than 10 and performed a more detailed fit of the sources. By freeing these parameters and refitting the sources we try to maximize the likelihood with respect to the model parameters which are free. The sources with a weak detection, that is TS less than 5, were removed from the model. A table of all the sources in the ROI are given in Appendix C.

Model Parameters from the fit:

Name : 3FGL J2032.2+4126

RA : 308.060°

DEC : 41.447°

GLON : 80.218°

GLAT : 1.019°

TS : 11293.55

Flux : 2.333e-08 +/- 3.68e-10 (cm² s)

EnergyFlux : 6.155e-05 +/- 1.04e-06 (MeV cm² s)

SpatialModel : PointSource

SpectrumType : PLSuperExpCutoff

4.5 MAPS

Maps based on 10 years of data for the energy range of 1 GeV to 500 GeV are produced based on the model parameters obtained from the fit. The counts map of the region is shown in Figure 4.1. The three bright pulsars are clearly seen to be much brighter than the rest of the sources in the region. They are J2032.2+4126, J2021.1+3651 and J2021.5+4026(γ Cygni)

Various residual maps of the region are shown in figure 4.2 4.3, 4.4 and 4.5. It can be seen

Figure 4.1: Counts Map - Full Phase: Total Counts map of the region, smoothed with a gaussian of 0.25 degrees radius.

seen from the figure 4.2 and 4.4 that even after subtracting all the sources, there is still a significant amount of signal left in the residual maps. Thus, the tool `find_sources` was used to add sources which had a high TS value. It uses peak detections to find new sources for the sources that have TS higher than the threshold specified. It also refits the spectral parameters of these new sources. Although we try to rectify the excess count by this method, it is not able to account for all of the excess counts in the ROI. A more efficient way to get more accurate results could be to develop better background models.

Figure 4.2: Residual Significance Map - Full Phase: Residual Significance map of the ROI after subtracting all the known sources

Figure 4.3: Residual Significance Map - Full Phase: Residual Significance map of the ROI after subtracting all the known sources except for J2032.2+4126

Figure 4.4: Residual Map - Full Phase: Residual map of the excess photon counts remaining after subtracting all the known sources in the ROI

Figure 4.5: Residual Map - Full Phase: Residual map of the excess photon counts remaining after subtracting all the known sources in the ROI except for J2032.2+4126

4.6 Spectral Energy Distribution Analysis

The Fermi-LAT sources were fit with one of three spectral types: a power law (PL, Equation 4.5), a log parabola (LP, Equation 4.6), or (in the case of identified pulsars as in the 3FGL) a power law with exponential cutoff (PLEC, Equation 4.7).

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\gamma} \quad (4.5)$$

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_b} \right)^{-\gamma - \beta \ln(\frac{E}{E_b})} \quad (4.6)$$

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right) \quad (4.7)$$

where N_0 is the differential flux normalization (prefactor), E_0 is the pivot energy, E_b is the break value energy and E_c the energy of the spectral cutoff energy.

PSR J2032.2+4126 was fit by a Power law with exponential cutoff. The Spectral energy diagram with upper limits is shown in the figure 4.3. The upper limits were selected for sources with TS less than the value of 6.

Figure 4.6: Spectral Energy Diagram(SED) - Full Phase: SED over energy range from 1 GeV to 500 GeV. The dashed(- -) line represents the fit line and the upper and lower bold lines indicate 1σ error. The data points are the flux in each energy bin with error bars. The upper limits were plotted for all points with TS less than 6

Spectral Parameters:

Prefactor(N_0) : $1.435\text{e-}11 \pm 3.929\text{e-}13$ (ph cm² s¹ MeV¹)

Index1(γ) : -1.568 ± 0.06357

Scale(E_0) : 1560 (fixed) MeV

Cutoff(E_c) : 5650 ± 487.8 MeV

Index2(β) : 1 (fixed)

From the SED for PSR J2032.2+4126, we can see that it exhibits a spectral cut-off.

As mentioned earlier, J2032.2+4126 lies in the Cygnus OB2 region where very fast,

vela type pulsars are expected to be created in the explosions of massive stars in the region²⁷. It also exhibits a double peak light curve which is consistent with the nature of high energy pulsars. This is consistent with the results obtained by Fermi where most Pulsars exhibit an exponential cut-off at a few GeVs in their spectra as discussed in Section 2.2.1 of Chapter 2.

Chapter 5

Phase Resolved Analysis

5.1 Event Weighting

Phase resolved analysis or the pulsar gating analysis is the process of reducing the flux of a bright pulsar from a region of interest²⁰. To carry out pulsar gating analysis, the first important step was to assign a pulse phase to every event in the events file based on the timing information available from the events file. The timing information was taken from "2PC_auxiliary_files_v04". The first step towards the calculation of the pulse phase was event weighting. The events that have a high probability of being photons are selected using the 'gtselect' tool. In step, along with the location and time window of the data, energy range and zenith angle cut of 90 degrees was applied

so as to reject the background gamma rays from earth. The value of 90 degrees is the one recommended by the LAT team for analysis above 100 MeV²⁰.

Once the data selection was successfully executed, 'gtmktime' tool was used to further filter out the data to make sure that only the events during which the satellite was working properly were used to maintain a high quality of data. This information is provided by the spacecraft file. A diffuse response for every event selected was then calculated using the 'gtdiffresp' tool²¹. Maximum Likelihood techniques is used to model LAT data. The distribution of photons for a given source model is the convolution of the model with the instrument response function. The diffuse response is calculated for every individual photon as an integral of source model with the instrument response calculated at the direction of incoming photon, energy range and time period. The diffuse response is calculated for every diffuse source in the model, which was three in this case. These diffuse responses are then used for calculation the probability for each photon which is calculated using "gtsrcprob" tool. This probability is the likelihood of a photon having originated from PSR J2032.2+4126, and not from the diffuse sources such as galactic and extragalactic diffuse emission or any other diffuse sources in the ROI.

The probability calculation is one of the important steps in the phase analysis. With the probability information at hand, three cuts of 25% probability, 50% probability, and 75% probability, where the probability is of the photon having originated from

the pulsar, were applied to analyze which parameters provided with better selection criteria for the on and off peak selection. The final selection was made based on the pulse phase information calculated in the next section.

5.2 TEMPO 2

The Fermi plug-in for TEMPO2⁹ facilitates the calculation of the rotational phase of the pulsar for each incoming photon. The first step is to calculate the position of the observatory for the time of arrival of each photon. This then helps in the conversion of the topocentric event date to the barycentric dates and thus calculate the pulse phase.

5.2.1 Time Correction

The timing model gives a corrected time of arrival for every event using the formula

$$t_{psr} = t_{obs} - \Delta_{\odot} - \Delta_{IS} - \Delta_B \quad (5.1)$$

where:

t_{psr} is the time of emission at pulsar (corrected time of arrival)

t_{obs} is the time of arrival at observatory

$\Delta_{\odot}$ is the transformation to solar system barycenter(SSB) frame

Δ_{IS} is the transformation to binary barycenter(BB) frame

Δ_B is the transformation to the pulsar frame

5.2.1.1 Solar system barycenter(SSB) frame ($\Delta_{\odot}$) correction

Coordinate time in the frame of the Solar system barycentre (SSB) is the proper time that would be measured by an observer located at the Solar system barycentre where the gravitational field of the sun and planets is not present²⁴.

This includes the coordinate transformation to the SSB frame, which accounts for vacuum propagation delays associated with the Earths orbital motion and the spin, precession and nutation of Earth and the excess delays owing to the passage of the signal through the Earths atmosphere and the Solar system²⁴.

The observational arrival time at the observatory is first corrected to the terrestrial time which ranges from 63 to 65 seconds approximately. This is then converted to the frame of solarsystem barycenter which typically a few milliseconds³⁵

5.2.1.2 Binary barycentre (BB) frame (Δ_{IS}) Correction

This is the frame that moves with the pulsar, or if it is a member of a binary system, the binary barycentre (BB). Coordinate time in this frame would be equal to the proper time of an observer at the origin of the frame, where the gravitational field of the pulsar and its companion are not present²⁴.

This includes the transformation to the binary barycenter(BB) frame, which accounts for vacuum propagation delays due to the motion of the system and the excess propagation delays due to passage of the signal through the interstellar medium. The size of this correction depends on the binary parameters¹¹

5.2.1.3 Pulsar Frame (Δ_B) Correction

Coordinate time in this frame is the proper time measured at the pulsar, or more precisely at its centre, where its gravitational field is not present²⁴.

This includes the transformation to the pulsar frame, which accounts for vacuum delays due to the binary orbital motion and the excess delays due to passage of the signal through the gravitational field of the companion²⁴.

5.3 Phase Calculation

Phase for every event is calculated by a Taylor expansion:

$$\phi(t) = \sum_{n \geq 1} \frac{\nu^{(n-1)}}{n!} (t_{psr} - t_p)^n + \phi_0. \quad (5.2)$$

where " ν " is pulsar spin frequency, t_0 is epoch(reference) time at which $\dot{\phi} = \nu$ and ϕ_0 is defined at the reference time of arrival and 'n' is the number of turns(rotation).

The gtpphase tool calculates the pulsar phase for each count in an event file. The timing ephemeris were derived from the ".par" files in the 2PC_auxiliary_files_v04.tgz files from the Second Pulsar Catalog¹¹. The phase information helps with the detection of the On-pulse and Off-Pulse region of the pulsar. By identifying the on-pulse region separately, it is possible to reduce the emission from the pulsar thus reducing the contamination of the nearby sources. Based on the probability cuts of 25% probability, 50% probability and 75% probability the data was trimmed with events only higher than the given probability cut were selected. The higher the probability the more the chances of the photons to have originated from the Pulsar. With a higher probability, even though the chances of only accounting for photons originating from Pulsar increase, there's also a possibility of losing out on real photon events with

lower probabilities and thus getting a wrong position of the peak for on pulse phase of pulsar. Thus I tested all three to check the difference in the location of the on-pulse peak when two gaussian peaks were fit to the phaseogram of Pulse phase as shown in Figure 5.1. The parameters for all the fits are displayed in Appendix A.

Figure 5.1: The two peaks are seen in the Phaseogram which represent the high intensity of flux during the on-pulse phase, a two peak gaussian was fit to the data selected after 25% probability cut. The width of both the gaussians was found to be 0.02(on the scale of Pulse Phase from 0 to 1) and the position of the peaks is at (0.108 ± 0.001) w.r.t. Pulse phase and (0.615 ± 0.001) w.r.t. pulse phase, the reduced chisquare value was 1.64

The Gaussian fit was performed using equations 5.2, 5.3 and 5.4.

$$f(x) = \frac{A1}{(\sigma1 * \sqrt{(2\pi)})} * \exp(-(x - x1) \frac{2}{(2*\sigma1^2)}) \quad (5.3)$$

$$f(y) = \frac{A2}{(\sigma2 * \sqrt{(2\pi)})} * \exp(-(x - x2) \frac{2}{(2*\sigma2^2)}) \quad (5.4)$$

$$f(z) = f(x) + f(y) \tag{5.5}$$

where A_1 and A_2 are the amplitudes of the peaks, x_1 and x_2 are their positions, σ_1 and σ_2 are the width of the peaks 1 and 2 respectively.

The peak positions and width of the peaks for the three data sets with different probability cuts were almost the same and fit the the uncertainty values. Here the trade off is between a larger data set to a better signal to noise ratio. Since with all the three cuts the results didn't change much for the location and width of peaks, I decided to go ahead with the 25% probability cut so that I had more data available for further analysis.

5.4 Pulsar gating or Phase resolved analysis

Pulsar gating analysis was carried out by dividing the data in the On-pulse and off-pulse regions. The ON-pulse region was defined using these phaseograms to contain most of the ON-pulse emission, with the region defined conservatively to minimise the contamination of the pulsar flux into the OFF-pulse region. Then, using only data from the time periods covered by the pulsar ephemeris. Due to the gated analysis, the analysis results suffer from reduced exposure time after phase cuts. In order to account for the reduced exposure time, I divided the On-Pulse data set by 0.17 and the Off-Pulse data set by 0.64 to normalize everything to account for the time lost.

The spectral energy distribution in both On-Pulse and Off-pulse regions is shown in figure 5.2 and 5.3 respectively.

Figure 5.2: Spectral Energy Diagram(SED) - On Pulse: SED for On-pulse phase over energy range from 1 GeV to 500 GeV. The dashed(- -) line represents the fit line and the upper and lower bold lines indicate 1σ error. The data points are the flux in each energy bin with error bars. The upper limits were plotted for all points with TS less than $4(2\sigma)$. The flux is divided by 0.17 to account for the time loss due

On comparing the SEDs of Full phase, On-pulse and Off-pulse, it is seen that the spectrum shifts up in the on-pulse phase and downwards in the off-pulse phase as compared to the full phase. This shows that the intensity of the Pulsar did reduce in the off pulse region.

Figure 5.3: Spectral Energy Diagram(SED) - Off Pulse: SED Off-pulse phase over energy range from 1 GeV to 500 GeV. The dashed(- -) line represents the fit line and the upper and lower bold lines indicate 1σ error. The data points are the flux in each energy bin with error bars. The upper limits were plotted for all points with TS less than $4(2\sigma)$. The flux is divided by 0.17 to account for the time loss due

Chapter 6

Results and Conclusion

The spectrum was plotted in comparison to the 3FGL and 4FGL catalog spectra along with the spectra produced by the analysis carried out in Abeysekara et al., 2018¹². The figure 5.4 shows this comparison of spectra.

It can be seen that the spectra produced by the fit parameters from Abeysekara et al.¹² and 3FGL catalog, a four year point source catalog of high energy Gamma-ray sources detected by Fermi-LAT, overlap whereas the Spectra from this analysis overlaps greatly with the 4FGL catalog, a eight year point source catalog of high energy Gamma-ray sources detected by Fermi-LAT,. Both Abeysekara et al. and 3FGL catalog use Pass 7 data along with a different galactic diffuse emission model, whereas both this study and the 4FGL catalog use Pass 8 data, which has an improved

Figure 6.1: Spectral Energy Diagram comparison

method of reconstruction of the events and more importantly an improved galactic diffuse emission model. The spectral parameters for all the three spectra from 3FGL¹², 4FGL²⁵ and Abeysekara et al¹² are provided in Appendix B.

The separation of the on-pulse and off-pulse region was implemented using the 2σ cut for on-pulse region and beyond 3.5σ for off-pulse. The region between 2σ and 3.5σ considered to be mid region and those events were dropped. The results match the published spectra of various studies which is shown in the figure 6.1.

A comparison plot is shown in Appendix D.1 which displays a bar plot of energy flux of the sources in all three regions, full phase, on-pulse and off-pulse. This is plotted

to prove that inspite of the phase cuts, the fit and flux measurement of other sources in the region is not majorly affected.

6.1 Conclusion

For this method to work, the ON-pulse flux needs to be steady over time. Also, there was no major effect on the Flux of surrounding sources in the region of interest due to the phase cuts, which proves that the Pulsar gating technique can be very useful for the analysis of fainter sources in the surrounding regions of a pulsar.

The main motivation behind this analysis was to be able to analyze the cocoon region that has lies three very bright pulsars in it's vicinity which dominate the emission from this region. To be able to perform an analysis that would provide with the Off-pulse regions of these Pulsars will greatly help in the further analysis of cocoon. This analysis was successfully able to reduce the emission from J2032.2+4126 with the help of Pulsar gating analysis by obtaining the On-Pulse and Off-Pulse information for the Pulsar.

This analysis can now be used as a prototype to perform Pulsar gating analysis on two other bright Pulsars in the Cygnus region, namely, J2021.1+3651 and J2021.5+4026 (γ Cygni) and subsequently to others. With the help of the Off-Pulse information from all these three pulsars, it will be possible for Binita Hina and Dr. Henrike Fleischhack to better understand the background in the extended emission analysis from the cocoon region.

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Appendix A

γ -ray Pulsars in Cygnus region

Source	l[°]	b[°]
FGL J2006.3+3103	68.7	-0.55
3FGL J1952.9+3253	68.78	2.83
3FGL J1958.6+2845	65.88	-0.35
3FGL J2017.9+3627	74.54	0.41
3FGL J2021.1+3651	75.23	0.11
3FGL J2030.0+3642	76.13	-1.43
3FGL J2030.8+4416	82.35	2.89
3FGL J2032.2+4126	80.22	1.02
PSR J1952+3252	68.76	2.82
PSR J2006+3102	68.67	-0.53

Table A.1

Gamma ray pulsars found in the Cygnus region in the Survey of Cygnus
Region by VERITAS¹³

Appendix B

Spectral best fit parameters for 3FGL¹², 4FGL²⁵ and Abeysekara et al¹²

Veritas fit parameters:

Prefactor = $1.08\text{e-}11 \pm 5\text{e-}13$ (ph cm² s¹ MeV¹)

index1 = 1.03 ± 0.12

cutoff = 3650 ± 380 MeV

Scale = 1560 MeV

3FGL fit parameters:

$$\text{Prefactor} = 1.165\text{e-}11 \text{ +/- } 3.11\text{e-}13 \text{ (ph cm}^2 \text{ s}^1 \text{ MeV}^1\text{)}$$

$$\text{index1} = 1.4622 \text{ +/- } 0.0552$$

$$\text{cutoff} = 4500 \text{ +/- } 407 \text{ MeV}$$

$$\text{Scale} = 1560 \text{ MeV}$$

4FGL fit parameters:

The Powerlaw with exponential cutoff equation was modifies in 4FGL catalog. It is as follows:

$$\frac{dN}{dE} = K \left(\frac{E}{E_0} \right)^{-\Gamma} \exp(a(E_0^b - E^b)) \quad (\text{B.1})$$

$$\text{Prefactor} = 5.6895\text{e-}12 \text{ +/- } 1.2064\text{e-}13 \text{ (ph cm}^2 \text{ s}^1 \text{ MeV}^1\text{)}$$

$$\text{index1} = 1.0161 \text{ +/- } 0.0755)$$

$$a = 0.00773 \text{ +/- } 0.00049)$$

$$b = 0.6667$$

$$\text{Scale} = 2235.47 \text{ MeV}$$

Appendix C

All the sources in ROI

Source name
3FGL J2032.2+4126
3FGL J2028.6+4110e
3FGL J2032.5+4032
3FGL J2037.4+4132c
3FGL J2028.5+4040c
3FGL J2039.4+4111
3FGL J2038.4+4212
3FGL J2036.8+4234c
PS J2040.1+4153
3FGL J2023.5+4126
3FGL J2034.6+4302
3FGL J2026.8+4003
PS J2024.9+3959
3FGL J2042.4+4209
3FGL J2032.5+3921
3FGL J2021.5+4026
3FGL J2021.0+4031e

Table C.1

Name of all the Sources present in the Region of Interest

Source name
3FGL J2033.3+4348c
PS J2020.0+4045
3FGL J2018.6+4213
3FGL J2030.8+4416
3FGL J2034.4+3833c
3FGL J2043.1+4350
3FGL J2022.2+3840
PS J2044.2+4415
3FGL J2018.5+3851
3FGL J2024.6+3747
3FGL J2048.8+4436
3FGL J2030.0+3642
3FGL J2035.0+3634
3FGL J2021.1+3651
PS J2016.2+3713
3FGL J2058.0+4347
3FGL J2015.6+3709
PS J2037.2+4650
PS J2022.1+3609
3FGL J2017.9+3627
3FGL J2000.1+4212
3FGL J2001.1+4352
3FGL J2012.0+4629
PS J2102.0+3840
3FGL J2041.1+4736
PS J2013.3+3615
3FGL J2014.4+3606
PS J2017.3+3526

Table C.2

Name of all the Sources present in the Region of Interest(continued)

Source name
PS J2026.6+3448
3FGL J1958.6+3844
3FGL J2102.3+4547
PS J2009.9+3544
PS J2109.6+3954
3FGL J2035.8+4902
PS J2102.0+4701
3FGL J2102.8+4704
3FGL J1953.3+3847
3FGL J2025.2+3340
3FGL J2028.3+3332
3FGL J2108.0+3654
3FGL J2111.4+4605
PS J2004.9+3419
PS J1958.7+3509
3FGL J2045.2+5026e
3FGL J2110.3+3540
3FGL J2004.4+3338
3FGL J2117.6+3725
3FGL J2023.2+3154
3FGL J1952.9+3253

Table C.3
Name of all the Sources present in the Region of Interest(continued)

Appendix D

Flux Measurements of all sources in ROI

Figure D.1: Flux Comparison - the grouped barchart compares plots the flux for every source for full phase, off pulse and on pulse data along with the error in the flux. All of these values are taken from the model parameters produced after the fit

Figure D.2: Flux Comparison - the grouped barchart compares plots the flux for every source for full phase, off pulse and on pulse data along with the error in the flux. All of these values are taken from the model parameters produced after the fit(continued)

Figure D.3: Flux Comparison - the grouped barchart compares plots the flux for every source for full phase, off pulse and on pulse data along with the error in the flux. All of these values are taken from the model parameters produced after the fit(continued)