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OBSERVATIONS OF PWNE WITH THE FERMI GAMMA-RAY  
SPACE TELESCOPE

A DISSERTATION  
SUBMITTED TO THE DEPARTMENT OF PHYSICS  
AND THE COMMITTEE ON GRADUATE STUDIES  
OF STANFORD UNIVERSITY  
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FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY

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I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

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Approved for the University Committee on Graduate Studies

# Abstract

*Two things fill the mind with ever-increasing wonder and awe, the more often and the more intensely the mind of thought is drawn to them: the starry heavens above me and the moral law within me.” – Immanuel Kant*

The launch of the *Fermi* Gamma-ray space telescope in 2008 offered an unprecedented view into the  $\gamma$ -ray sky.

All the things we can learn with the Large Area Telescope (LAT)

Development of a new analysis method for studying spatially-extended Pulsar Wind Nebulae (PWNe) using **pointlike**.

A monte-carlo validation of the analysis method.

Search for new spatially-extended sources with the LAT.

Observations of PWNe in the off-peak region of LAT detected pulsars.

Search for PWNe counterparts to TeV sources.

Using the population of PWNe to understand the radiation mechanism of PWNe.

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# List of Acronyms

The following acronyms are used in this text, and are included here for reference:

**SA** Solid Angle

**LAT** Large Area Telescope

**PWN** Pulsar Wind Nebula

**IC** Inverse Compton

**2FGL** The Second Fermi-LAT catalog

**CGS** The Centimetre-Gram-Second System of Units

**PL** power law

**ECPL** exponentially-cutoff power law

# Chapter 1

## Overview

In Chapter 2, we discuss the history of  $\gamma$ -ray astrophysics, ...

# Chapter 2

## Gamma-ray Astrophysics

### 2.1 The History of Gamma-ray Detectors

- Prior predictions by Feenberg & Primakoff
- Why Gamma-rays can't make it to the ground
- OSO-3
- SAS-2
- EGRET
- AGILE

#### 2.1.1 The *Fermi* Gamma-ray Space Telescope

...

#### 2.1.2 H.E.S.S.

...

## 2.2 Gamma-ray Sources Astrophysics

### 2.2.1 Pulsars

Describe pulsar physics. See description from Carroll and Ostlie page 593

$$\dot{E} = 4\pi^2 I \dot{P} / P \quad (2.1)$$

$$\tau_c = P / 2\dot{P} \quad (2.2)$$

### 2.2.2 Pulsar Wind Nebulae

### 2.2.3 Supernova Remnants

## 2.3 Radiation Processes in Gamma-ray Astrophysics

- The non-thermal radiation processes typical in astrophysics are most commonly

### 2.3.1 Synchrotron

### 2.3.2 Inverse Compton

Inverse Compton (IC) emission is ...

### 2.3.3 Bremsstrahlung

### 2.3.4 $\pi^0$ Decay

## 2.4 Modeling the Galactic Diffuse and Isotropic Gamma-ray Background

- Historical Observations of galactic diffuse emission



- GALPROP model of diffuse emission. Reference: <http://arxiv.org/abs/1202.4039>
- Empirical Ring model of galactic diffuse emission.
- The isotropic background: <http://arxiv.org/abs/1002.3603>
- Galactic diffuse emission is primarily composed of ...
- Something about how great galprop is.
- Something about

## 2.5 Sources Detected by the Fermi LAT

- A variety of sources detected by the LAT:

### 2.5.1 The Second Fermi-LAT catalog (2FGL)

2FGL was a catalog by the LAT collaboration containing XXX Sources.

#### Describe Catalog

- Citation is Nolan et al. (2012)
- Source classification method
- Number of sources detected by the Large Area Telescope (LAT)
- Forward reference Chapter 3, which does a more thorough description of likelihood analysis method.
- Source classes/associations

### 2.5.2 The Second Fermi Pulsar Catalog

- Process of detecting Pulsars with the LAT
- Number of pulsars detected by the LAT

### 2.5.3 PWNe Detected by the LAT

Crab

Vela X

MSH 15-52

HESS J1825

HESS J1857

2FGL J1857 + 026

1. Reference is Rousseau et al. (2012)
2. <http://arxiv.org/pdf/1206.3324v1.pdf>

## Chapter 3

# Maximum-likelihood analysis of LAT data

In this chapter, we discuss maximum-likelihood analysis, the principle analysis method used to perform spectral and spatial analysis of LAT data. In Section 3.1, we discuss the reasons necessary for employing this analysis procedure compared to other simpler analysis methods. In Section 3.2, we describe the benefits of a maximum-likelihood analysis. In Section 3.3, we discuss the steps involved in defining a complete model of the sky, a necessary part of any likelihood analysis.

In Section 3.5, we discuss the standard implementation of binned maximum likelihood in the LAT Science Tools and in particular the tool `gtlike`. In Section 3.6, we then discuss the `pointlike` package, an alternate package for maximum-likelihood analysis of LAT data. We discuss the similarities and differences between `pointlike` and `gtlike`.

In the next chapter (Chapter 4), we will discuss the addition of capability into `pointlike` for studying spatially-extended sources and the analysis method which will be used in this paper to study spatially-extended sources.

We note that much of the notation and formulation of likelihood analysis in this chapter follows Kerr (2011).

### 3.1 Motivations for Maximum-Likelihood Analysis of Gamma-ray Data

Traditionally, spectral and spatial analysis of astrophysical data relies on a process known as aperture photometry. In this process, a source in the data is analyzed by directly measuring the number of photons coming from the object. This process is done by measuring the counts within a given radius of the source and subtracting from it a background level estimated from a nearby region. Often, the source's flux is calibrated by measurements of nearby objects with known fluxes. Otherwise, the flux can be obtained from by dividing the number of counts from the source by the telescope's size, the observation time, and the telescope's conversion efficiency.

Similarly, for faint sources the statistical significance of the detection can be obtained from the Poisson nature of the data. For TeV experiments such as H.E.S.S., this analysis method is described in Li & Ma (1983).

Unfortunately, this simpler analysis method is inadequate for dealing with the complexities introduced in analyzing LAT data.

Most importantly, aperture photometry assumed that the background is isotropic so that the background level below the source can be estimated from nearby regions. As was discussed in Section 2.4, the Galactic diffuse emission is highly anisotropic, rendering this assumption invalid.

In addition, this method is not optimal due to the high density of sources detected in the Gamma-ray sky. 2FGL reported on the detection of 1873 sources, which corresponds to an average source spacing of  $\sim 5^\circ$ . But within the inner  $45^\circ$  of the galactic plane in longitude and  $0.5^\circ$  of the galactic plane in latitude, there are 73 sources, corresponding to a source density of  $\sim 1$  source per square degree. The aperture photometry method is unable to effectively fit multiple sources when the tails of the PSF overlap and furthermore make background estimation problematic.

Finally, this method is suboptimal due to the large energy range of LAT observations. A typical spectral analysis studies a source from an energy of 100 MeV to energies above 100 GeV. Similarly, as was shown in , the PSF of the LAT is rather broad ( $\gtrsim 1^\circ$ ) at low energy and much narrower ( $\sim 0.1^\circ$ ) at higher energies. Therefore,

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there is a much higher sensitivity to the higher energy photons coming from a source. But simple aperture photometry method would ignore this improvement by weighting each photon equally.

## 3.2 Description of Maximum-Likelihood Analysis

The field of  $\gamma$ -ray astrophysics has generally found maximum-likelihood to be a dependable method to avoid the issues discussed above. The term likelihood was first introduced by Fisher (1925). Maximum-likelihood was applied to photon-counting experiments in the context of astrophysics by Cash (1979). Mattox et al. (1996) described the maximum-likelihood analysis framework developed to analyze EGRET data.

In the formulation, one relies upon primarily upon the likelihood function. The likelihood, denoted  $\mathcal{L}$ , is quite simply the probability of obtaining the observed data given an assumed model:

$$\mathcal{L} = P(\text{data}|\text{model}) \quad (3.1)$$

Section 3.3 will provide describe the components that go into a model of the data.

Generally, a model of the sky depends upon a list of parameters that we denote as  $\vec{\lambda}$ . Therefore, the likelihood function itself becomes a function of the parameters of the model:

$$\mathcal{L} = \mathcal{L}(\vec{\lambda}) \quad (3.2)$$

The term maximum-likelihood refers to the fact that the best-fit parameters of a model can be estimated by maximizing the likelihood function.

What are the benefits of maximum likelihood

Describe Wilk's Theorem and its application to parameter error estimation

## 3.3 Defining a Model of the Sources in the Sky

In order to perform a maximum-likelihood analysis, one requires a parameterized model of the sky. A model of the sky is composed of a set of  $\gamma$ -ray sources, each

characterized by its photon flux density  $\mathcal{F}(E, t, \vec{\Omega}|\vec{\lambda})$ . This represents the number of photons emitted per unit energy, per unit time, per units solid angle at a given energy, time, and position in the sky. In The Centimetre-Gram-Second System of Units (CGS), it has units of  $\text{ph cm}^{-2}\text{s}^{-1}\text{erg}^{-1}\text{sr}^{-1}$ .

Often, the spatial and spectral part of the source model are separable and independent of time. When that is the case, we like to write the source model as

$$\mathcal{F}(E, t, \vec{\Omega}|\vec{\lambda}) = \frac{dN}{dE} \times \text{PDF}(\vec{\Omega}). \quad (3.3)$$

Here,  $\frac{dN}{dE}$  is only a function of energy and  $\text{PDF}(\vec{\Omega})$  is only a function of position ( $\vec{\Omega}$ ). In this formulation, some of the model parameters  $\vec{\lambda}$  are taken by the  $\frac{dN}{dE}$  function and some by the  $\text{PDF}(\vec{\Omega})$  function. In CGS,  $\frac{dN}{dE}$  is in units of  $\text{ph cm}^{-2}\text{s}^{-1}\text{erg}^{-1}$ .

The spectrum  $\frac{dN}{dE}$  is typically modeled by simple geometric functions. The most popular spectral model is a power law (PL):

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\gamma} \quad (3.4)$$

Here,  $\frac{dN}{dE}$  is a function of energy and also fo the two model parameters (the prefactor  $N_0$  and the spectral index  $\gamma$ ). The parameter  $E_0$  is often called the energy scale or the pivot energy and is not considered a model parameter.

Another common spectral model is the broken-power-law spectral model

$$\frac{dN}{dE} = N_0 \times \begin{cases} (E/E_b)^{\gamma_1} & \text{if } E < E_b \\ (E/E_b)^{\gamma_2} & \text{if } E \geq E_b \end{cases} \quad (3.5)$$

This model represents a powerlaw with an index of  $\gamma_1$  which has a break at energy  $E_b$  to having an index of  $\gamma_2$ .

Finally, the exponentially-cutoff power law (ECPL) spectral model is often used to model the  $\gamma$ -ray emission from pulsars:

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{\gamma} \exp \left( -\frac{E}{E_c} \right). \quad (3.6)$$

For energies much below  $E_c$ , the ECPL is a PL with spectral index  $\gamma$ . For energies much larger than  $E_c$ , the ECPL exponentially decreases.

PDF represents the spatial distribution of the emission. It is traditionally normalized as though it was a probability:

$$\int d\Omega \text{PDF}(\vec{\Omega}). \quad (3.7)$$

Therefore, in CGS PDF has units of  $\text{sr}^{-1}$ . For a point-like source at a position  $\vec{\Omega}'$ , the spatial model is:

$$\text{PDF}(\vec{\Omega}) = \delta(\vec{\Omega} - \vec{\Omega}') \quad (3.8)$$

and is a function of the position of the source. Example spatial models for spatially-extended sources will be presented in section XXXXX.

This formulation assumed that the source models are not time dependent. This is traditionally because it is difficult to find simple parameterized models to fit the time behavior of a variable source. Instead, the typical strategy to fit variable sources is to divide a large range of time into multiple smaller time intervals and to perform multiple likelihood fits in each time range.

In some situations, the spatial and spectral part of a source do not nicely decouple. An example of this could be **SNR!**s (**SNR!**s) which could show a spectral variation across the source. s14 (????) and Hewitt et al. (2012) have simplified this problem by a simple method which has been adopted to study this kind of source.

**FINISH DISCUSSION**

In situations where spatial and spectral components couple, typical to make multiple spatial templates, each with an independent spectra (e.g. the Puppis A paper's fitting multiple hemispheres).

Discuss how diffuse background is more complicated and requires a mapcube.

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### 3.4 The LAT Instrument Response Functions

The performance of the LAT is composed of two effects. The efficiency of the LAT refers to its ability to reconstruct a photon which comes into the detect. The dispersion of the LAT refers to the probability of misreconstructing an event.

The efficiency is typically called the effective area. We write it as  $\epsilon(E, t, \vec{\Omega})$ . It is a function of energy, time, and Solid Angle (SA). It is measured in units of area ( $\text{cm}^2$ ).

LINK TO [arXiv:1206.1896](https://arxiv.org/abs/1206.1896) for MORE THOUROUGH DISCUSSION OF EFFECTIVE AREA

DISCUSS HOW EFFECTIVE AREA IS A FUNCTION OF DIFFERENT THINGS

The dispersion is the probability of a photon with true energy  $E$  and incoming direction  $\vec{\Omega}$  at time  $t$  being reconstructed to have an energy  $E'$ , an incoming direction  $\vec{\Omega}'$  at a time  $t'$ . The dispersion is written as  $P(E', t', \vec{\Omega}' | E, t, \vec{\Omega})$ . It represents a probability and is therefore normalized such that

$$\int \int \int dE d\Omega dt P(E', t', \vec{\Omega}' | E, t, \vec{\Omega}) = 1 \quad (3.9)$$

What is the range of the integrals

Therefore,  $P(E', t', \vec{\Omega}' | E, t, \vec{\Omega})$  has units of 1/energy/SA/time

We assume these two factors to decouple and write the LAT's instrument response as

$$R(E', \vec{\Omega}', t' | E, \vec{\Omega}, t) = \epsilon(E, t, \vec{\Omega}) P(E', t', \vec{\Omega}' | E, t, \vec{\Omega}) \quad (3.10)$$

Therefore, the instrument response has units of area/energy/SA/time

The convolution of the flux of a model with the instrument response produces the expected counts per unit energy/time/SA begin reconstructed to have an energy  $E'$  at a position  $\vec{\Omega}'$  and at a time  $t'$ :

$$\tau(E', \vec{\Omega}', t' | \vec{\lambda}) = \int \int \int dE d\Omega dt \mathcal{F}(E, t, \vec{\Omega} | \vec{\lambda}) R(E', \vec{\Omega}', t' | E, \vec{\Omega}, t) \quad (3.11)$$



Here, this integral is performed over all true energies, SAs, and times for which the source model has support.

For LAT analysis, we conventionally make the simplifying assumption that the energy, spatial, and time dispersion decouple:

$$P(E', t', \vec{\Omega}' | E, t, \vec{\Omega}) = \text{PSF}(\vec{\Omega}' | E, \vec{\Omega}) \times E_{\text{disp}}(E' | E) \times T_{\text{disp}}(t' | t) \quad (3.12)$$

Here, PSF is the point-spread function and represents ...

BETTER DISCUSSION OF PSF OF THE LAT, WHAT ITS SCALE IS...

$E_{\text{disp}}$  represents the energy dispersion of the LAT. The energy dispersion of the LAT is a function of both the incident energy and incident angle of the photon. It varies from  $\sim 5\%$  to  $20\%$ , degrading at lower energies due to energy losses in the tracker and at higher energy due to electromagnetic shower losses outside the calorimeter. Similarly, it improves for photons with higher incident angles that are allowed a longer path through the calorimeter (Ackermann et al. 2012).

For sources with smoothly-varying spectra, the effects of ignoring the inherent energy dispersion of the LAT are typically small. Ackermann et al. (2012) performed a monte carlo simulation to show that for power-law point-like sources, the bias introduced by ignoring energy dispersion was on the level of a few percent. Therefore, energy dispersion is typically ignored for standard likelihood analysis:

$$E_{\text{disp}} = \delta(E - E') \quad (3.13)$$

We caution that for analysis of sources extended to energies below 100 MeV and for sources expected to have spectra that do not smoothly vary, the effects of energy dispersion could be more severe.

- $T_{\text{disp}}$  is the time dispersion.
- \_\_\_\_\_
- The timing dispersion is  $< 10 \mu\text{s}$  Atwood et al. (2009)
- WRITE ENERGY DISPERSION AS A DELTA FUNCTION

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Therefore, the instrument response is typically approximated as

**FINISH**

$$R(E', \vec{\Omega}', t' | E, \vec{\Omega}, ) = \epsilon(E, t', \vec{\Omega}) \text{PSF}(\vec{\Omega}' | E, \vec{\Omega}) \quad (3.14)$$

The expected count rate is then typically integrated over time to compute the total counts. Assuming that the source model is time independent, we get:

$$\tau(E', \vec{\Omega}' | \vec{\lambda}) = \int d\Omega \mathcal{F}(E, \vec{\Omega} | \vec{\lambda}) \left( \int dt \epsilon(E, t, \vec{\Omega}) \right) \text{PSF}(\vec{\Omega}' | E, \vec{\Omega}) \quad (3.15)$$

This equation essentially says that the counts expected by the LAT for the particular model is the product of the source's flux with the effective area and then convolved with the point-spread function.

Figure out how the  $\theta$  dependence of the IRFs factors into this calculation

### 3.5 Binned Maximum-Likelihood of LAT Data with the Science Tools

- For a standard LAT analysis, we perform a binned maximum-likelihood analysis:
- In the standard science tools, the data is binned in position and energy. and integrated in energy.
- For time-series analysis, typically a time-summed analysis is performed successivly in multiple time bins.
- The likelihood comes from a sum over each bin
- The likelihood is defined as

$$\mathcal{L} = \prod_j \frac{\theta_j^{n_j} e^{-\theta_j}}{n_j!} \quad (3.16)$$

– Here,  $j$  is a sum over position/energy bins.

- $\theta_j$  is the counts predicted by the model, which is defined following the discussion in Section 3.3.
- $n_j$  are the observed counts in the spatial/energy bin  $j$
- The model counts are computed by integrating the differential counts defined in Equation 3.11 over the energy bin:

$$\theta_{ij} = \int_j dE d\Omega dt \tau(E, \vec{\Omega}, t | \vec{\lambda}_i) \quad (3.17)$$

Here,  $j$  represents the integral over the  $j$ th position/energy bin,  $i$  represents the  $i$ th source, and  $\vec{\lambda}_i$  refers to the parameters defining the  $i$ th source. The total model counts is computed by summing over all sources:

$$\theta_j = \sum_i \theta_{ij} \quad (3.18)$$

- In the standard *Fermi* science tools, the binning of photons over position in the sky and energy to compute  $n_j$  is done with `gtbin`.
- In the standard *Fermi* science tools, the model counts  $\theta_j$  are computed in several steps ...
- The instrument response is computed with a combination of `gtltcube`, `gtexpcube`.
- Convert a model of the sky into model predicted counts
- poisson likelihood
- Particular implementation of maximum likelihood analysis
- Describe `gtbin`, `gtselect`, `gtlike`

Write Section or Perform simple MC Simulation to demonstrate significance of detection

### 3.6 The Alternate Maximum-Likelihood Package `pointlike`

- Developed for Speed
- Sparse Matrices,
- Methods for computing integral model counts.

## Chapter 4

# Analysis of Spatially Extended LAT Sources

### 4.1 Analysis Method

### 4.2 Validation of the TS Distribution

### 4.3 Extended Source Detection Threshold

### 4.4 Testing Against Source Confusion

### 4.5 Test of 2LAC Sources

### 4.6 Systematic Errors on Extension

## Chapter 5

# Search for Spatially-extended Sources

### 5.1 Extended Source Search Method

### 5.2 New Extended Sources

### 5.3 Discussion

## Chapter 6

# Search for PWNe associated with Gamma-loud Pulsars

### 6.1 Off-peak Phase Selection

### 6.2 Off-peak Analysis Method

### 6.3 Off-peak Results

### 6.4 Off-Peak Individual Source Discussion

# Chapter 7

## Search for PWNe associated with TeV Pulsars

Notes

- Only include sources classified as PWN in TeVCat.
- Always model LAT Pulsar in the background (???)

### 7.1 List of Candidates

### 7.2 Analysis Method

### 7.3 Sources Detected



## Chapter 8

### Search for PWNe associated with High $\dot{E}$ Pulsars

## Chapter 9

# Population Study of LAT-detected PWNe

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