

# Todo list

Why do we discard energy dispersion. Find reference. . . . .	6
Why discard time dispersion . . . . .	6

OBSERVATIONS OF PWNE WITH THE FERMI GAMMA-RAY  
SPACE TELESCOPE

A DISSERTATION  
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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 LAT

Development of a new analysis method for studying spatially-extended 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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# Contents

<b>Abstract</b>	<b>iv</b>
<b>Acknowledgement</b>	<b>v</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Gamma-ray Detectors . . . . .	1
1.1.1 The <i>Fermi</i> Gamma-ray Space Telescope . . . . .	1
1.1.2 H.E.S.S. . . . .	1
1.2 Galactic Gamma-ray Astrophysics . . . . .	1
1.2.1 Pulsars . . . . .	1
1.2.2 Pulsar Wind Nebulae . . . . .	1
1.2.3 Supernova Remnants . . . . .	1
1.3 Radiation Processes . . . . .	1
1.3.1 Synchrotron . . . . .	2
1.3.2 Inverse Compton . . . . .	2
1.3.3 Bremsstrahlung . . . . .	2
1.3.4 $\pi^0$ Decay . . . . .	2
1.4 Modeling the Galactic Diffuse and Isotropic Gamma-ray Background	2
1.5 Sources Detected by the Fermi LAT . . . . .	2
1.5.1 The Second Fermi-LAT Source Catalog . . . . .	2
1.5.2 The Second Fermi Pulsar Catalog . . . . .	3
1.5.3 PWN Detected by the LAT . . . . .	3



<b>2</b>	<b>Maximum-likelihood analysis of LAT data</b>	<b>4</b>
2.1	Motivations for Maximum-Likelihood Analysis of Gamma-ray Data . . . . .	4
2.2	Defining a Model of the Sources in the Sky . . . . .	5
2.3	The LAT Instrument Response Functions . . . . .	5
2.4	Application of Binned Maximum-Likelihood to LAT Data with the Science Tools	7
2.5	The Alternate Maximum-Likelihood Package <code>pointlike</code> . . . . .	8
2.6	Extended Source Analysis in <code>pointlike</code> . . . . .	8
<b>3</b>	<b>Search for Spatially-extended Sources</b>	<b>9</b>
3.1	Analysis Method . . . . .	10
3.2	Validation of the TS Distribution . . . . .	10
3.3	Extended Source Detection Threshold . . . . .	10
3.4	Testing Against Source Confusion . . . . .	10
3.5	Test of 2LAC Sources . . . . .	10
3.6	Systematic Errors on Extension . . . . .	10
3.7	Extended Source Search Method . . . . .	10
3.8	New Extended Sources . . . . .	10
3.9	Discussion . . . . .	10
<b>4</b>	<b>Search for PWNe associated with Gamma-loud Pulsars</b>	<b>11</b>
<b>5</b>	<b>Search for PWNe associated with TeV Pulsars</b>	<b>12</b>
5.1	List of Candidates . . . . .	12
5.2	Analysis Method . . . . .	12
5.3	Sources Detected . . . . .	12
<b>6</b>	<b>Search for PWNe associated with High Edot Pulsars</b>	<b>13</b>
<b>7</b>	<b>Population Study of LAT-detected PWNe</b>	<b>14</b>

# List of Tables

# List of Figures

# Chapter 1

## Introduction

### 1.1 Gamma-ray Detectors

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

#### 1.1.2 H.E.S.S.

### 1.2 Galactic Gamma-ray Astrophysics

#### 1.2.1 Pulsars

#### 1.2.2 Pulsar Wind Nebulae

#### 1.2.3 Supernova Remnants

### 1.3 Radiation Processes

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

### 1.3.1 Synchrotron

### 1.3.2 Inverse Compton

### 1.3.3 Bremsstrahlung

### 1.3.4 $\pi^0$ Decay

## 1.4 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

## 1.5 Sources Detected by the Fermi LAT

- A variety of sources detected by the LAT:

### 1.5.1 The Second Fermi-LAT Source Catalog

- Citation is Nolan et al. (2012)
- Source classification method
- Number of sources detected by the LAT

- Forward reference Chapter 2, which does a more thorough description of likelihood analysis method.
- Source classes/associations

### 1.5.2 The Second Fermi Pulsar Catalog

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

### 1.5.3 PWN 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 2

## Maximum-likelihood analysis of LAT data

- The notation and terminology in this section is primarily taken from Kerr (2011).

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

- Traditional astrophysical analysis involves an on minus of background estimation.
- Analysis of LAT data more complicated due to:
  - Anisotropic background. See Section 1.4.
  - Energy-dependent PSF
  - High source density, especially in the Galactic plane.
- To avoid issues associated with this, we perform a maximum likelihood analysis
- Define a model of the sky.
- likelihood  $L$  is defined as  $L = P(data|model)$ , where  $L = L(model\ parameters)$ .

- Benefits: XXX

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

- Each source can be characterized by its photon flux density  $\mathcal{F}(E, t, \vec{\Omega}|\vec{\lambda})$ . This is the number of photons emitted per unit energy, time, into a unit solid angle  $d\Omega$  at a given energy, time, and position  $\vec{\Omega}$  in the sky.
- Typically, spatial and spectral model's are indepdnet of time with the spatial and spectral component decopuling:

$$\mathcal{F}(E, t, \vec{\Omega}|\vec{\lambda}) = A(E)B(\vec{\Omega}) \quad (2.1)$$

Presumably,  $A$  takes in some of the  $\vec{\lambda}$  parameters and  $B$  takes in the other parameters.

- In situations where there is a time dependence, likelihoood assuming constant source is performed in smaller time bins.
- In situations where spatial and spectral components couple, typical to make multiple spatial templates, each with an indepdnet spectra (e.g. the Puppis A paper's fitting multiple hemispheres).
- Discuss how diffuse background is more complciated.
- Show some examples spectral models: point source, extended source.

## 2.3 The LAT Instrument Response Functions

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

The efficiency is written as  $\epsilon(E, t, \vec{\Omega})$  and is measured in units of area ( $\text{cm}^2$ ).



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

$$\int \int \int dE d\Omega dt P(E', t', \vec{\Omega}' | E, t, \vec{\Omega}) = 1 \quad (2.2)$$

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

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

$$R(E', \vec{\Omega}', t' | E, \vec{\Omega}, t) = \epsilon(E, t, \vec{\Omega}) P(E', t', \vec{\Omega}' | E, t, \vec{\Omega}) \quad (2.3)$$

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

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

$$\tau(E', \vec{\Omega}', t' | \vec{\lambda}) = \int \int \int dE d\Omega dt \mathcal{F}(E, t, \vec{\Omega} | \vec{\lambda}) R(E', \vec{\Omega}', t' | E, \vec{\Omega}, t) \quad (2.4)$$

Here, this integral is performed over all true energies, solid angles, 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:

$$P(E', t', \vec{\Omega}' | E, t, \vec{\Omega}) = \text{PSF}(\vec{\Omega}' | E, \vec{\Omega}) \times E_{\text{disp}}(E' | E) \times T_{\text{disp}}(t' | t) \quad (2.5)$$

Here, PSF is the point-spread function and represents

$E_{\text{disp}}$  is the energy dispersion. \_\_\_\_\_

$T_{\text{disp}}$  is the time dispersion. \_\_\_\_\_

Why  
do we  
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Find

## 2.4 Application of Binned Maximum-Likelihood to 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

$$\mathcal{L} = \prod_j \frac{\theta_j^{n_j} e^{-\theta_j}}{n_j!} \quad (2.6)$$

- Here,  $j$  is a sum over position/energy bins.
- $\theta_j$  is the counts predicted by the model, which is defiend followign the discussion in Section 2.2.
- $n_j$  are the observed counts in the spatial/energy bin  $j$
- The model counts are computed by integrating the differential counts defined in Equation 2.4 over the energy bin:

$$\theta_{ij} = \int_j dE d\Omega dt \tau(E, \vec{\Omega}, t | \vec{\lambda}_i) \quad (2.7)$$

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 parmeters defining the  $i$ th source. The total model counts is computed by summing over all sources:

$$\theta_j = \sum_i \theta_{ij} \quad (2.8)$$

- 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`

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

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

## 2.6 Extended Source Analysis in `pointlike`



## Chapter 3

# Search for Spatially-extended Sources

### 3.1 Analysis Method

### 3.2 Validation of the TS Distribution

### 3.3 Extended Source Detection Threshold

### 3.4 Testing Against Source Confusion

### 3.5 Test of 2LAC Sources

### 3.6 Systematic Errors on Extension

### 3.7 Extended Source Search Method

### 3.8 New Extended Sources

### 3.9 Discussion

## Chapter 4

# Search for PWNe associated with Gamma-loud Pulsars

## Chapter 5

# Search for PWNe associated with TeV Pulsars

### 5.1 List of Candidates

### 5.2 Analysis Method

### 5.3 Sources Detected

## Chapter 6

# Search for PWNe associated with High Edot Pulsars



## Chapter 7

# Population Study of LAT-detected PWNe

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