

Todo list

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
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Joshua Jeremy Lande

February 2013

© Copyright by Joshua Jeremy Lande 2013
All Rights Reserved

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.

(Stefan Funk) Principal Adviser

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.

(Elliott Bloom)

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.

(Roger Romani)

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 γ -ray sky.

All the things we can learn with the **LAT!** (**LAT!**)

Development of a new analysis method for studying spatially-extended **PWN!**s (**PWN!**s) using **pointlike**.

A monte-carlo validation of the analysis method.

Search for new spatially-extended sources with the **LAT!**.

Observations of **PWN!**s in the off-peak region of **LAT!** detected pulsars.

Search for **PWN!**s counterparts to TeV sources.

Using the population of **PWN!**s to understand the radiation mechanism of **PWN!**s.

Acknowledgement

Acknowledge the educational institutes which taught me physics: My high school HB Woodlawn, my undergraduate institution Marlboro College, and my Stanford University.

First, I would like to acknowledge those mentors who inspired me to get a PhD.

- Mark Dodge, my high school physics teacher.
- Ron Turner, my internship adviser at Analytic Services (ANSER) during the GWU Science and Engineering Apprentice Program (SEAP)
- Anthony Tyson at UC Davis for my SULI Internship
- Apurva Mehta and Sam Webb sam Web at SLAC SULI Internship.

During my PhD I was helped by an almost overwhelminlgy large number of people in the **LAT!** collaboration.

People at Stanford/SLAC: Stefan Funk, Elliott Bloom, Markus Ackermann, Tobias Jogler, Junichiro Katsuta, Yasunobu Uchiyama, Seth Digel, James Chiang

pointlike collaborators: Matthew Kerr, Toby Burnett, Eric Wallace, Marshall Roth

Pulsar Collaborators: David Smith, Matthew Kerr, Peter den Hartog, Tyrel Johnson, Damien Parent, Ozlem Celik

Careful review of text: Jean Ballet, Johann Cohen-Tanugi

I would like to thank the **PWN!**s people Thank the people in Bordeaux: Marianne Lemoine-Goumard, Romain Rousseau, and Marie-Hélène Grondin

Fermi SLAC Grad Students: Keith Bechtol, Alex Drlica-Wagner, Alice Allafort, Herman Lee Yvonne Edmonds, Bijan Berenji, Ping Wang, Warit Mitthumsiri

Joanne Bogart, Heather Kelly, Richard Dubois, Renata Dart, Stuart Marshall, and Glenn Morris for putting up with my computer problems.

Martha Siegel, Chris Hall, Ziba Mahdavi, awesome SLAC administrators. Maria Frank, Elva Carbajal, and Violet Catindig , awesome Stanford administrators.

Additional Astro Stanford Graduate Students: Helen Craig, Michael Shaw, Adam Van Etten, Kyle Watters

Additonal Graduate Students at Stanford: Dan Riley, Joel Frederico, Ahmed Ismail, Joshua Cogan, Kunal Sahasrabuddhe,

Contents

List of Tables

List of Figures

List of Acronyms

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

LAT Large Area Telescope

PWN Pulsar Wind Nebula

Chapter 1

Overview

In Chapter ??, we discuss the history of γ -ray astrophysics, . . .

Chapter 2

Gamma-ray Astrophysics

2.1 Astronomy and the Atmosphere

Humans surely have, since the very beginning, stared into space and contemplated its brilliance. Stone circles in the Nabta Playa in Egypt are likely the first observed astronomical observatory and are believed to have acted as a prehistoric calendar. Dating back to the 5th century BC, they are 1,000 years older than stonehenge (?).

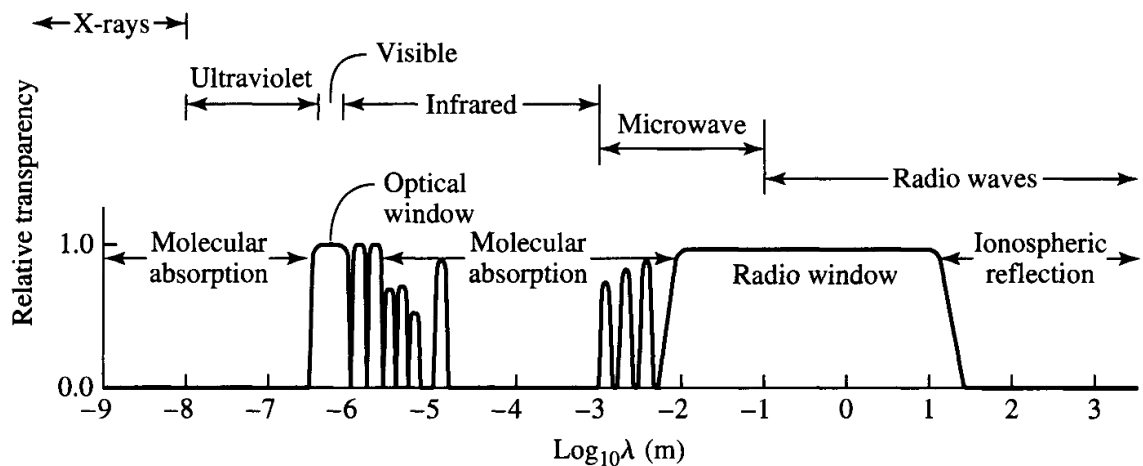


Figure 2.1 Transparency of the atmosphere of the earth to photons of varying wavelengths. This figure is from ?

Astronomy has historically been almost entirely concerned with studying the photons that arrive from outer space. Because of their charge neutrality, photons are not deflected by intergalactic electric and magnetic fields and therefore point back to the objects emitting them.

Historically, the field of astronomy concerned the study of visible light. The reason for this is visible light is not significantly absorbed in the atmosphere. In addition to the visible spectrum, radio waves, some energies of infrared radiation, and long-wavelength ultraviolet radiation can be measured from the ground. Figure ?? shows the transparency of the atmosphere of the earth to photons of different wavelengths.

Slowly, over time, astronomers expanded their view across the electromagnetic spectrum. First, the astronomical observations were made from the ground. Infrared radiation from the sun was first observed by William Herschel in 1800. Herschel measured this infrared radiation by measuring the temperature of sunlight through a prism and extending the measurement past the red part of the spectrum (?). The first extraterrestrial source of radio waves was detected by Jansky in 1933. Jansky, a radio engineer at Bell labs, was studying the origins of radio interference when he detected radio emission towards the center of our galaxy. (?).

The expansion of the astronomical frontier to other wavelengths required the development of rockets and satellites in the 20th century. The first ultraviolet observation of the sun was performed in 1946 from a captured V-2 rocket (?). Observations of solar x-rays were also first carried out on a captured V-2 Rocket in 1949 (?).

2.2 The History of Gamma-ray Astrophysics

It was only natural to wonder about photons with even higher energies. These higher energy photons must come from more extreme processes in space.

As is common in the field of physics, the prediction of the detection of cosmic γ -rays far preceded their discovery. ? theorized that the interaction of starlight with cosmic rays could produce γ -rays through IC! (IC!) upscattering. Following the discovery of the neutral pion in 1949, ? predicted that γ -ray emission could be

observed from the decay of neutral pions when cosmic rays interacted with interstellar matter. And in the same year, ? discussed the bremsstrahlung radiation of cosmic-ray electrons. ? first predicted the detection of several sources of γ -rays including solar flares, **PWN!**s (**PWN!**s), and active galaxies.

Attempts were made in the 1940s and 1950s to determine the composition of cosmic rays using balloon-based experiments. See, for example ? and ?. But the attempt to observe cosmic γ -rays was hampered by the strong background of atmospheric albedo γ -rays.

The first space-based γ -ray detector was Explorer XI ?. It was developed at **MIT!** (**MIT!**) under the direction of William L. Kraushaar. It employed a sandwich scintillator and a Cherenkov counter to direct the position and energy of incoming γ -rays and was surrounded by a plastic anticoincidence scintillation counter. The sandwich detector had an area of $\sim 45\text{cm}^2$, but an effective area of only $\sim 7\text{cm}^2$, corresponding to a detector efficiency of $\sim 15\%$.

What was the energy range of explorer ii

It was launched on board Explorer XI on April 27, 1961. The instrument was in operation for 7 months, but only 141 hours of data were of acceptable quality. Using these observations, Explorer XI observed 31 γ -rays and, because the distribution a distribution of these γ -rays was consistent with being isotropic, the experiment could not firmly identify the γ -rays as being cosmic in nature.

Describe scintillation detector better. Read William Tomkin's thesis, page 8.

The first definitive detection of γ -ray came in 1962 by an experiment on the Ranger 3 moon probe (?). It detected an isotropic flux of γ -rays in the 0.5 MeV to 2.1 MeV energy range.

OSO-3! (**OSO-3!**), also developed by Kraushaar, followed Explorer XI as the next major astrophysical γ -ray detector ?. The **OSO-3!** satellite allowed the on board γ -ray detected to have an improved weight, power, telemetry, and exposure, creating a more sensitive experiment. The experiment operated in the energy range from 50 MeV to ~ 400 MeV and had an effective area $\sim 9\text{cm}^2$.

It was launched on March 8, 1967 and operated for 16 months, measuring 621 cosmic γ -rays. The most important result of the experiment was to measure a strong

anisotropy in the distribution of the γ -rays with a strong clustering of γ -rays towards the Galactic plane. Figure ?? shows a skymap of these γ -rays. This experiment confirmed both a Galactic component to the γ -ray sky as well as an additional isotropic component, hypothesised to be extragalactic in origin.

What was the PSF of OSO-3? could it be pointed?

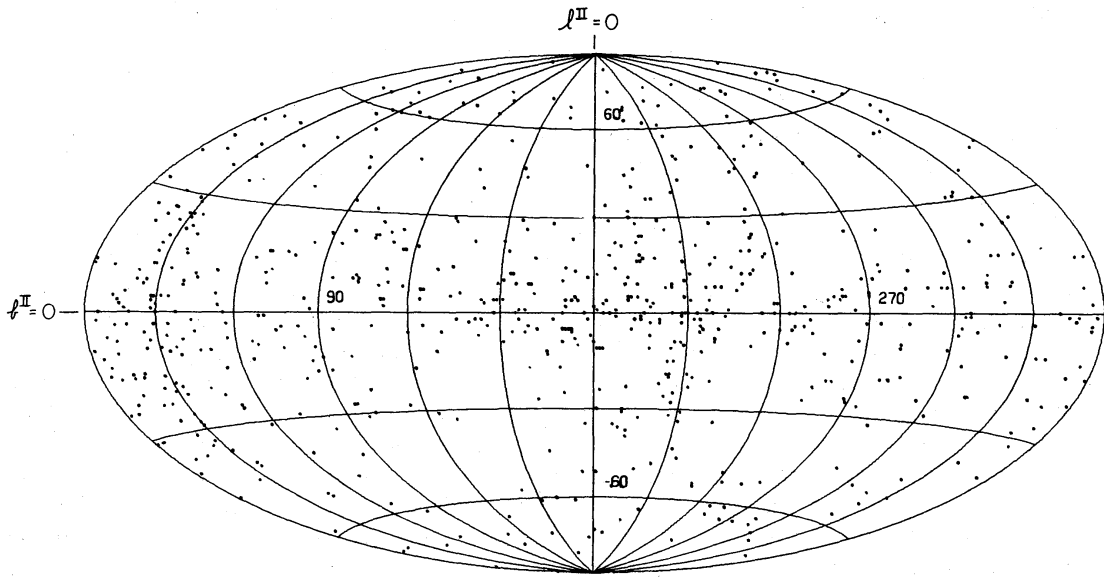


Figure 2.2 The position of all 621 cosmic γ -rays detected by **OSO-3!**. This figure is from ?.

The major discovery by **OSO-3!** was confirmed by a balloon-based γ -ray detector in 1970 (?). In the following year, the first γ -ray pulsar (the Crab) was detected by another balloon-based detector ?.

The next major advancement in γ -ray astronomy came from the **SAS-2!** (**SAS-2!**) and COS-B missions.

SAS-2! was a dedicated γ -ray detector launched by **NASA!** (**NASA!**) in November 15, 1972. **SAS-2!** was ? It improved upon **OSO-3!** by incorporating a spark chamber and having an overall larger size. The size of the active area of the detector was 640 cm^2 and the experiment had a much improved effective area of $\sim 115 \text{ cm}^2$. The spark chamber allowed for a separate measurement of the electron and positron

tracks, which allowed for improved directional reconstruction of the incident γ -ray. **SAS-2!** had a PSF $\sim 5^\circ$ at 30 MeV and $\sim 1^\circ$ at 1 GeV.

SAS-2! collected data for over 6 months before a power supply failure ended data collection. **SAS-2!** Observed over 8,000 γ -ray photons covering $\sim 55\%$ of the sky including most of the Galactic plane. **SAS-2!** discovered strong emission along the Galactic plane and particularly towards the Galactic center. It also discovered pulsations from the Crab (?) and Vela pulsar (?). In addition, **SAS-2!** discovered Geminga, the first γ -ray source with no compelling multiwavelength counterpart (?). Geminga was eventually discovered to be a pulsar by **EGRET!** (**EGRET!**) (?) and retroactively by **SAS-2!** (?).

on August 9, 1975, **ESA!** (**ESA!**) launched COS-B, a γ -ray detector similar to **SAS-2!**. COS-B included a spark chamber but improved upon the design of **SAS-2!** by including a calorimeter below the spark chamber which improved the energy resolution to $< 100\%$ for energies ~ 3 GeV (?). COS-B has a comparable effective area to **SAS-2!**: $\sim 50 \text{ cm}^2$ at ~ 400 MeV (?).

Over what energy range did COS-B observe photons?

COS-B operated successfully for over 6 years and produced the first detailed catalog of the γ -ray sky. In total, COS-B observed $\sim 80,000$ photons ?. **2CG!** (**2CG!**) detailed the detection 25 γ -ray sources for $E > 100$ MeV (?). Figure ?? shows a map of these sources. Of these sources, the vast majority lay along the galactic plane and could not be positively identified with sources observed at other wavelengths. In addition, COS-B observed the first ever extragalactic γ -ray source, (3C273, ?).

EGRET! on board **CGRO!** (**CGRO!**)

Figure out of EGRET was first to detect a PWNe (crab nebula. EGRET analysis: <http://adsabs.harvard.edu/abs/1993ApJ...409..697N> COS-B Analysis: <http://adsabs.harvard.edu/abs/1987A%26A...174...85C>

How many γ -rays **EGRET!** detect?

How many pulsars did **EGRET!** detect?

- AGILE
- *Fermi*

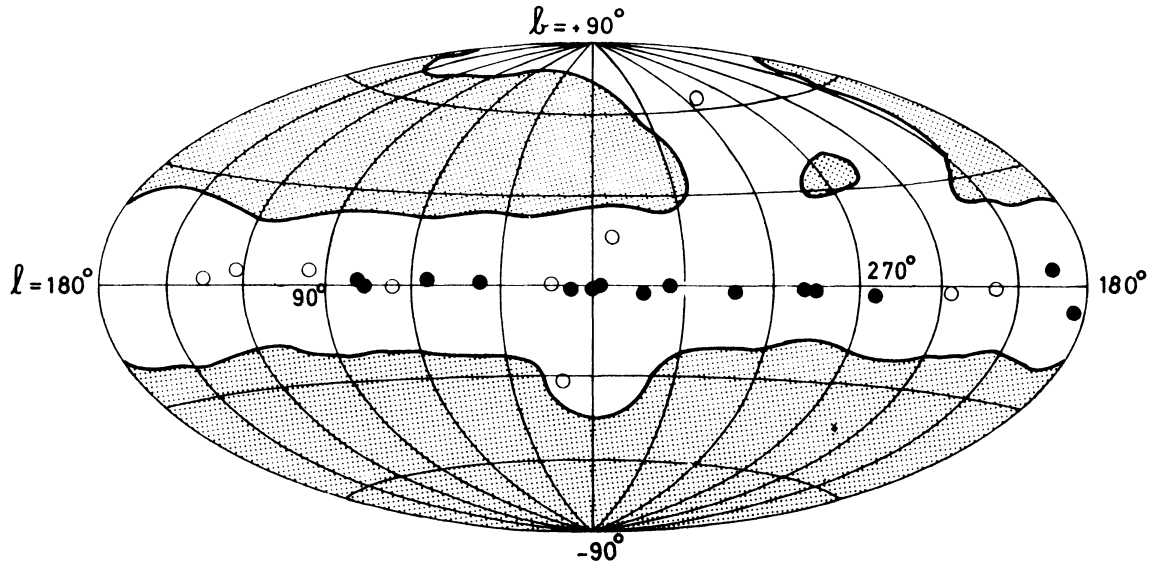


Figure 2.3 A map of the sources observed by COS-B. The filled circles represent brighter sources. The unshaded region corresponds to the parts of the sky observed by COS-B. This figure is from ?.

- Short description of the history of TeV astronomy

2.2.1 Pulsar Wind Nebulae

2.3 Astrophysical Sources of Gamma-ray

2.3.1 Pulsars

Pulsars were first discovered in 1967 by Jocelyn Bell Burnell and Antony Hewish (?). They had constructed a radio telescope that used interplanetary scintillation with the intention of observing quasars. In the process, they detected a source with a periodicity of 1.3 s.

Even before the discovery, ? had predicted the existence of neutron stars. Shortly

First
nebu-
lae?

following the 1967 discovery, ? and ? argued that the observed pulsar was a rotating neutron star.

The discovery of many more pulsars came quickly. In 1968, the Vela pulsar (?) and the Crab pulsar (?) were discovered.

The first pulsar observed at optical frequencies was the Crab, discovered in 1969 shortly after its radio discovery (?). In the same year, the first X-ray pulsations were discovered from the same source. At the time, there were no space-based X-ray observatories, so observations had to be performed from rockets. The discovery was carried out almost concurrently by a group at **NRL!** (NRL!) (?) and at **MIT!** (?). Using proportional counters, these experiments showed that the pulsed emission from the Crab extended to X-ray energies and that, for this source, the X-rays emission was a factor > 100 more energetic than the observed visible emission.

As was discussed in Section ??, γ -ray emission from the Crab was detected only 2 years later (?).

ATNF catalog?

EGRET pulsars?

The state of the art in γ -ray detection of pulsars will be included in an upcoming publication. 2PC: Section ??

When was the PSR, PWN connection made

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

First
gamma-
ray
detection

$$\dot{E} = -4\pi^2 I \dot{P} / P^3 \quad (2.1)$$

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

2.3.2 Supernova Remnants

2.4 The *Fermi* Gamma-ray Space Telescope

2.5 Radiation Processes in Gamma-ray Astrophysics

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

2.5.1 Synchrotron

2.5.2 IC!

IC! emission is ...

2.5.3 Bremsstrahlung

2.5.4 π^0 Decay

2.6 Modeling the Galactic Diffuse and Isotropic Gamma-ray Background

Include discussion of modeling, if time permitting

- Discuss the historical Observations of galactic diffuse emission

Mention how **OSO-3!** first detected the *gamma*-rays from the galaxy: Section ??.

- 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

2.7 Sources Detected by the Fermi LAT!

- A variety of sources detected by the **LAT!**:

2.7.1 2FGL! (2FGL!)

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

Describe Catalog

- Citation is ?
- Source classification method
- Number of sources detected by the **LAT!** (**LAT!**)
- Forward reference Chapter ??, which does a more thorough description of likelihood analysis method.
- Source classes/associations

2.7.2 The Second Fermi Pulsar Catalog

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

2.7.3 PWN!s Detected by the LAT!

Crab

Vela X

MSH 15-52

Dig up HESS reference of HESS J1514-59.

HESS J1825–137

HESS J1825–137 is a cool source

HESS Detection: HESS Energy dependent morphology: ?

LAT Detection: ?

HESS J1640–465

HESS J1640–465 is also cool.

HESS detection: ? Fermi detection: ?

2FGL J1857+026

2FGL J1857+026 is another good source.

LAT detection: ?

1. <http://arxiv.org/pdf/1206.3324v1.pdf>

J1023

...

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 ??, we discuss the reasons necessary for employing this analysis procedure compared to other simpler analysis methods. In Section ??, we describe the benefits of a maximum-likelihood analysis. In Section ??, we discuss the steps involved in defining a complete model of the sky, a necessary part of any likelihood analysis.

In Section ??, we discuss the standard implementation of binned maximum likelihood in the LAT Science Tools and in particular the tool `gtlike`. In Section ??, 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 ??), 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 ?.

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 ?.

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 ??, 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° of the galactic plane in longitude and 0.5° of the galactic plane in latitude, there are 73 sources, corresponding to a source density of ~ 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,

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 γ -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 ?. Maximum-likelihood was applied to photon-counting experiments in the context of astrophysics by ?. ? 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 ?? 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 γ -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 **CGS!** (**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 **PL!** (**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 γ). 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 **BPL!** (**BPL!**) 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 γ_1 which has a break at energy E_b to having an index of γ_2 .

Finally, the **ECPL!** (**ECPL!**) spectral model is often used to model the γ -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 γ . 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 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. ? and ? 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.

WHAT
SEC-
TION
DE-
SCRIBES
EX-
TENDED
SOURCE
PDFs

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 detector. 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 **SA!** (**SA!**). It is measured in units of area (cm^2).

LINK TO [arXiv:1206.1896](#) for MORE THOUROUGH DISCUSSION OF EFFEC-TIVE 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 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 $1/\text{energy}/\text{SA!}/\text{time}$

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 $\text{area}/\text{energy}/\text{SA!}/\text{time}$

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, **SA!**s, 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_{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 (?).

For sources with smoothly-varying spectra, the effects of ignoring the inherent energy dispersion of the LAT are typically small. ? 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_{disp} is the time dispersion.
-
- The timing dispersion is $< 10 \mu\text{s}$?

- **WRITE ENERGY DISPERSION AS A DELTA FUNCTION**

Therefore, the instrument response is typically approximated as

Why
dis-
card
time
dis-
per-
sion

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 θ 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.
- θ_j is the counts predicted by the model, which is defiend followign the discussion in Section ??.

- 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 ?? 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 θ_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 PWN!s 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 PWN!s 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 PWN!s associated with High \dot{E} Pulsars

Chapter 9

Population Study of LAT-detected PWNe

Chapter 10

Future Work (or Outlook)??

What would make good future work. Something about CTA population study, something about improved modeling liek HESS J1825, something about better PSF

Bibliography

- Ackermann, M., Ajello, M., Albert, A., et al. 2012, ApJS, 203, 4
- Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006a, A&A, 460, 365
- . 2006b, ApJ, 636, 777
- Arnold, J. R., Metzger, A. E., Anderson, E. C., & van Dilla, M. A. 1962, J. Geophys. Res., 67, 4878
- Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
- Baum, W. A., Johnson, F. S., Oberly, J. J., et al. 1946, Phys. Rev., 70, 781
- Bertsch, D. L., Brazier, K. T. S., Fichtel, C. E., et al. 1992, Nature, 357, 306
- Bignami, G. F., Boella, G., Burger, J. J., et al. 1975, Space Science Instrumentation, 1, 245
- Bradt, H., Rappaport, S., & Mayer, W. 1969, Nature, 222, 728
- Browning, R., Ramsden, D., & Wright, P. J. 1971, Nature Physical Science, 232, 99
- Burnight, T. 1949, Phys. Rev, 76, 19
- Carroll, B. W., & Ostlie, D. A. 2006, An Introduction to Modern Astrophysics, 2nd edn. (Benjamin Cummings)
- Cash, W. 1979, ApJ, 228, 939
- Cocke, W. J., Disney, M. J., & Taylor, D. J. 1969, Nature, 221, 525

- Critchfield, C. L., Ney, E. P., & Oleksa, S. 1952, *Physical Review*, 85, 461
- Feenberg, E., & Primakoff, H. 1948, *Phys. Rev.*, 73, 449
- Fichtel, C. E., Hartman, R. C., Kniffen, D. A., et al. 1975, *ApJ*, 198, 163
- Fisher, R. A. 1925, *Statistical Methods for Research Workers* (Edinburgh: Oliver and Boyd)
- Fritz, G., Henry, R. C., Meekins, J. F., Chubb, T. A., & Friedman, H. 1969, *Science*, 164, 709
- Gold, T. 1968, *Nature*, 218, 731
- Grondin, M.-H., Funk, S., Lemoine-Goumard, M., et al. 2011, *ApJ*, 738, 42
- Hayakawa, S. 1952, *Progress of Theoretical Physics*, 8, 571
- Herschel, W. 1800, *Philosophical Transactions of the Royal Society of London*, 90, pp. 284
- Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. 1968, *Nature*, 217, 709
- Hewitt, J., Grondin, M.-H., Lemoine-Goumard, M., et al. 2012
- Hulsizer, R. I., & Rossi, B. 1948, *Phys. Rev.*, 73, 1402
- Hutchinson, G. 1952, *Philosophical Magazine Series 7*, 43, 847
- Jansky, K. 1933, *Proceedings of the Institute of Radio Engineers*, 21, 1387
- Katsuta, J., Uchiyama, Y., Tanaka, T., et al. 2012
- Kerr, M. 2010, PhD thesis, University of Washington
- Kniffen, D. A., & Fichtel, C. E. 1970, *ApJ*, 161, L157
- Kraushaar, W., Clark, G. W., Garmire, G., et al. 1965, *ApJ*, 141, 845

- Kraushaar, W. L., Clark, G. W., Garmire, G. P., et al. 1972, *ApJ*, 177, 341
- Large, M. I., Vaughan, A. E., & Mills, B. Y. 1968, *Nature*, 220, 340
- Li, T.-P., & Ma, Y.-Q. 1983, *ApJ*, 272, 317
- Mattox, J. R., Bertsch, D. L., Fichtel, C. E., et al. 1992, *ApJ*, 401, L23
- Mattox, J. R., Bertsch, D. L., Chiang, J., et al. 1996, *ApJ*, 461, 396
- McK Mahille, J., Schild, R., Wendorf, F., & Brenner, R. 2007, *African Skies*, 11, 2
- Morrison, P. 1958, *Il Nuovo Cimento*, 7, 858
- Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, *ApJS*, 199, 31
- Pacini, F. 1967, *Nature*, 216, 567
- . 1968, *Nature*, 219, 145
- Rousseau, R., Grondin, M.-H., Van Etten, A., et al. 2012, *A&A*, 544, A3
- Slane, P., Castro, D., Funk, S., et al. 2010, *The Astrophysical Journal*, 720, 266
- Staelin, D. H., & Reifstein, III, E. C. 1968, *Science*, 162, 1481
- Swanenburg, B. N., Hermsen, W., Bennett, K., et al. 1978, *Nature*, 275, 298
- Swanenburg, B. N., Bennett, K., Bignami, G. F., et al. 1981, *ApJ*, 243, L69
- Thompson, D. J., Fichtel, C. E., Hartman, R. C., Kniffen, D. A., & Lamb, R. C. 1977a, *ApJ*, 213, 252
- Thompson, D. J., Fichtel, C. E., Kniffen, D. A., & Ogelman, H. B. 1977b, *ApJ*, 214, L17