Todo list

OBSERVATIONS OF PWNE WITH THE FERMI GAMMA-RAY SPACE TELESCOPE

A DISSERTATION
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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 γ-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 Compoton

Chapter 1

Overview

In Chapter 2, we discuss the history of γ-ray astrophysics, ...

Chapter 2

Gamma-ray Astrophysics

2.1 The History of Gamma-ray Detectors

2.1.1 The *Fermi* Gamma-ray Space Telescope

2.1.2 H.E.S.S.

2.2 Galactic Gamma-ray Astrophysics

2.2.1 Pulsars

2.2.2 Pulsar Wind Nebulae

2.2.3 Supernova Remenants

2.3 Radiation Processes

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

2.3.1 Synchrotron

2.3.2 Inverse Compoton

Inverse Compoton (IC) emission is ...

2.3.3 Bremsstrahlung

2.3.4 Pi0 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`
- Emperical Ring model of galactic diffuse emisson.
- 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 Source 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

$\mathrm{2FGL\,J1857+026}$

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 discuss the steps invovled in defining a complete model of the sky, a necessary part of any likelihood analysis.

In Section 3.4, we discuss the standard implementation of binned maximum likelihood in the LAT Science Tools and in particular the tool `gtlike`.

In Section 3.5, we then discuss the `pointlike` pacakge, an alterate package for maximum-likelihood analysis of LAT data. We discuss the similarities and differences between `pointlike` and `gtlike`.

We not 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

- Traditonal astrophysical analysis involves an on minus of background estimation.
- Analysis of LAT data more complciated due to:
  - Anisotrpic background. See Section 2.4.
  - Energy-dependent PSF
  - High source density, espeically in the Galactic plane.
- To avoid issues assocaited with this, we perform a maximum likelihood analysis
- Define a model of the sky.
- likelihood L is defiend as $L = P(data|model)$, where $L = L(modelparameters)$.
- What are the benefits of maximum likelihood
- How are errors computed using maximum likelihood
- How is statistical signifiance computed using maximum likelihood

3.2 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 indepndent of time with the spatial and spectral component decopuling:

$$\mathcal{F}(E, t, \vec{\Omega}|\vec{\lambda}) = A(E)B(\vec{\Omega}) \tag{3.1}$$

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.

3.3 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 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 (cm^2).

LINK TO arXiv: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 to have an energy E', an incomming 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

$$\int\int\int dE d\Omega dt P(E',t',\vec{\Omega}'|E,t,\vec{\Omega}) = 1 \tag{3.2}$$

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

$$R(E', \vec{\Omega}', t'|E, \vec{\Omega}, t) = \epsilon(E, t, \vec{\Omega})P(E', t', \vec{\Omega}'|E, t, \vec{\Omega}) \tag{3.3}$$

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':

$$\tau(E', \vec{\Omega}', t'|\vec{\lambda}) = \int\int\int dE\, d\Omega\, dt\, \mathcal{F}(E, t, \vec{\Omega}|\vec{\lambda})R(E', \vec{\Omega}', t'|E, \vec{\Omega}, t) \tag{3.4}$$

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:

$$P(E', t', \vec{\Omega}'|E, t, \vec{\Omega}) = \mathrm{PSF}(\vec{\Omega}'|E, \vec{\Omega}) \times \mathrm{E}_{\mathrm{disp}}(E'|E) \times \mathrm{T}_{\mathrm{disp}}(t'|t) \tag{3.5}$$

Here, PSF is the point-spread function and represents

$\mathrm{E}_{\mathrm{disp}}$ 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 calorimiter. Similarly, it improves for photons with higher incident angles that are allowed a longer path through the calorimieter (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 perect. Therefore, energy dispersion is typicially ignored for standard likelihood analysis:

$$\mathrm{E}_{\mathrm{disp}} = \delta(E - E') \tag{3.6}$$

We cauation 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.

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

Why discard time dispersion

Therefore, the instrument response is typically approximated as

$$R(E', \vec{\Omega}', t' | E, \vec{\Omega},) = \epsilon(E, t', \vec{\Omega})\mathrm{PSF}(\vec{\Omega}' | E, \vec{\Omega}) \tag{3.7}$$

FINISH

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

$$\tau(E', \vec{\Omega}' | \vec{\lambda}) = \int d\Omega\, \mathcal{F}(E, \vec{\Omega} | \vec{\lambda}) \left(\int dt\ \epsilon(E, t, \vec{\Omega}) \right) \mathrm{PSF}(\vec{\Omega}' | E, \vec{\Omega}) \tag{3.8}$$

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 depedence of the IRFs factors into this calcualtion

3.4 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-serires analysis, typically a time-summed analysyis is performed successivly in multiple time bins.
- The likelihood comes from a sum over each bin
- The likelihood is defined as

$$\mathcal{L} = \prod_j \frac{\theta_j^{n_j} e^{-\theta_j}}{n_j!} \tag{3.9}$$

  - 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 3.2.
  - 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 3.4 over the energy bin:

$$\theta_{ij} = \int_j dE\, d\Omega\, dt\, \tau(E, \vec{\Omega}, t|\vec{\lambda}_i) \tag{3.10}$$

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

$$\theta_j = \sum_i \theta_{ij} \tag{3.11}$$

- 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 implemenation of maximum likelihood anlaysis
- Describe `gtbin`, `gtselect`, `gtlike`

3.5 The Alternate Maximum-Likelihood Package `pointlike`

- Developed for Speed
- Sparce Matricies,
- Methods for computing integral model counts.

Chapter 4

Extended Source Analysis with `pointlike`

Chapter 5

Search for Spatially-extended Sources

5.1 Analysis Method

5.2 Validation of the TS Distribution

5.3 Extended Source Detection Threshold

5.4 Testing Against Source Confusion

5.5 Test of 2LAC Sources

5.6 Systematic Errors on Extension

5.7 Extended Source Search Method

5.8 New Extended Sources

5.9 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

7.1 List of Candidates

7.2 Analysis Method

7.3 Sources Detected

Chapter 8

Search for PWNe associated with High Edot Pulsars

Chapter 9

Population Study of LAT-detected PWNe

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