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

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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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(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 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 PWNs in the off-peak region of LAT detected pulsars.

Search for PWNs counterparts to TeV sources.

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

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List of Acronyms

2CG the second COS-B catalog. 8

2FGL the second *Fermi* catalog. 19, 22

2PC the second *Fermi* pulsar catalog. 19

ACD Anti-Coincidence Detector. 10

BPL broken-power law. 24

CGRO the Compton Gamma Ray Observatory. 8

CGS the Centimetre-Gram-Second System of Units. 24, 25

ECPL exponentially-cutoff power law. 24, 25

EGRET the Energetic Gamma Ray Experiment Telescope. 8

ESA the European Space Agency. 8

FWHM full width at half maximum. 6

GBM Gamma-ray Burst Monitor. 10

IC inverse Compoton. 5, 14

LAT Large Area Telescope. iv, v, 9, 19, 20, 36

MIT the Massachusetts Institute of Technology. 6, 10

NASA the National Aeronautics and Space Administration. 7

NRL the Naval Research Laboratory. 10

OSO-3 the Third Orbiting Solar Observatory. 6, 7, 18

PL power law. 24, 25

PWN pulsar wind nebula. iv, v, 6, 11, 15, 16, 20, 33–36

SA solid angle. 26, 27

SAS-2 the second Small Astronomy Satellite. 7, 8

SNR supernova remnant. 25

Chapter 1

Overview

In Chapter 2, 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 (McK Mahille et al. 2007).

Astronomy has historically been almost entirely concerned with studying the photons that arrive from outer space. Because of their charge neutrality, photons are not defected 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 signifcantly absorbed in the atmosphere. In addition to the visible spectrum, radio waves, some energies of infrared radiation, and long-wavelenth ultraviolet radiation can be measured from the ground. Figure Figure 2.1 shows the transparancy of the atmosphere of the earth to photons of differnet wavelenths.

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

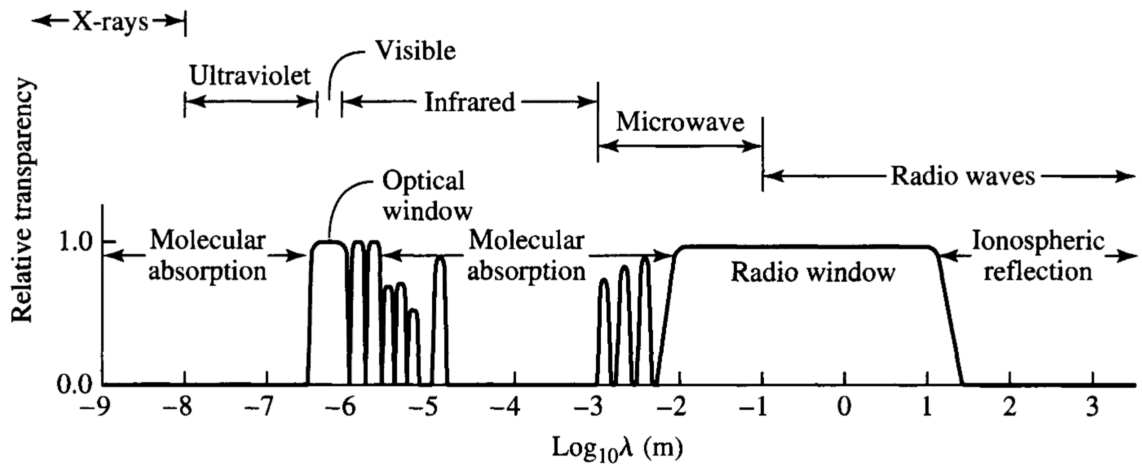

Figure 2.1: Transparency of the atmosphere of the earth to photons of varying wavelenthts. This figure is from Carroll & Ostlie (2006)

measured this infrared radiation by measuring the temperature of sunlight through a prisim and extending the measurement past the red part of the spectrum (Herschel 1800). The first extraterrestrial source of radio waves was detected by Jansky in 1933. Janksy, a radio engineer at Bell labs, was studying the origins of radio interference when he detected radio emission towards the center of our galaxy. (Jansky 1933).

The expansion of the astronomical fronteire to other wavelenths required the development of rockets and sattelites in the 20th ceuntry. The first ultraviolet observation of the sun was performed in 1946 from a captured V-2 rocket (Baum et al. 1946). Observations of solar x-rays were also first carried out on a captured V-2 Rocket in 1949 (Burnight 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 proceded their discovery. Feenberg & Primakoff (1948) theorized that the interaction of starlight with cosmic rays could produce γ-rays through inverse Compoton (IC) upscattering. Following the discovery of the neutral pion in 1949, Hayakawa (1952) 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, Hutchinson (1952) discussed the bremsstrahlung radiation of cosmic-ray electrons. Morrison (1958) first predicted the detection of several sources of γ-rays including solar flares, pulsar wind nebulae (PWNe), 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 Critchfield et al. (1952) and Hulsizer & Rossi (1948). 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 Kraushaar et al. (1965). It was developed at the Massachusetts Institute of Technology (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 surounded by a plastic anticoincidence scintilation counter. The sandwich detector operated in the energy energy range for $E > 100\,\mathrm{MeV}$. It had an area of $\sim 45\mathrm{cm}^2$ but an effective area of only $\sim 7\mathrm{cm}^2$, corresonding to a detector efficiency of $\sim 15\%$.

It was launched on boad Explorer XI on April 27, 1961. The instrument was in opreation 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 scintilation 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 (Arnold et al. 1962). It detected an isotropic flux of γ-rays in the 0.5 MeV to 2.1 MeV energy range.

The Third Orbiting Solar Observatory (OSO-3), also developed by Kraushaar, followed Explorer XI as the next major astrophysical γ-ray detector Kraushaar et al. (1972). OSO-3 allowed the on board γ-ray detected to have an improved weight, power, telemetry, and expsoure, creating a more sensitive experiment. The experiment operated in the energy range from 50 MeV to $\sim$ 400 MeV, had an effective area $\sim$ 9 cm^2, and had a angular resolution of $\sim$ 24° at its full width at half maximum (FWHM).

It was launched on March 8, 1967 and operated for 16 months, measuring 621 cosmic γ-rays. The most important result of the expirment was to measure a strong anisotrophy in the distribution of the γ-rays with a strong clustering of γ-rays towards the Galactic plane. Figure 2.2 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.

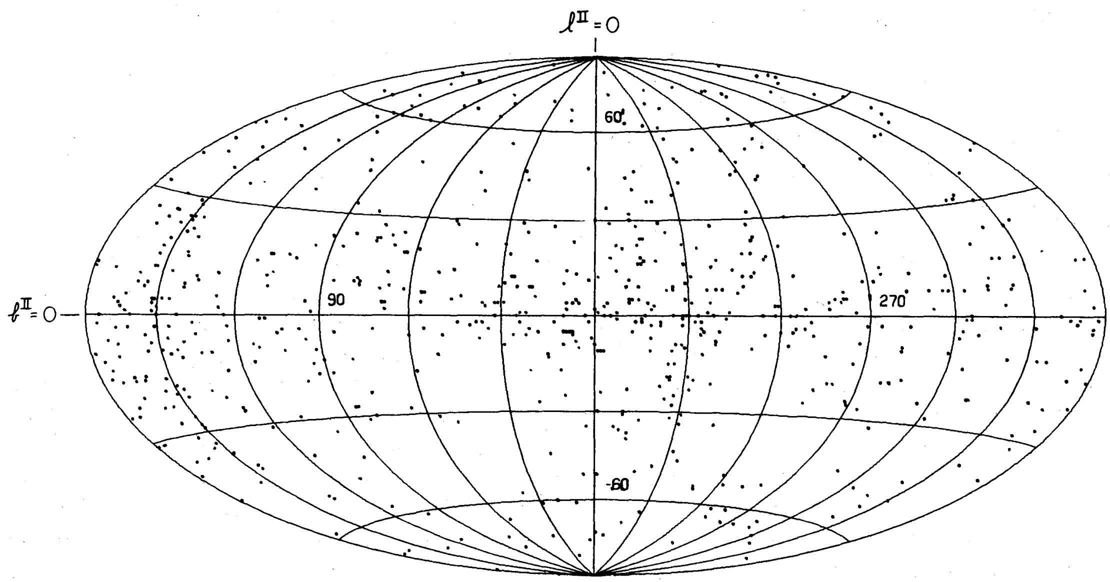

Figure 2.2: The position of all 621 cosmic γ-rays detected by OSO-3. This figure is from Kraushaar et al. (1972).

The major discovery by OSO-3 was confirmed by a ballon-based γ-ray detector in 1970 (Kniffen & Fichtel 1970). In the following year, the first γ-ray pulsar (the Crab) was detected by another ballon-based detector Browning et al. (1971).

The next major advancement in γ-ray astronomy came the second Small Astronomy Satellite (SAS-2) and COS-B.

SAS-2 was a dedicated γ-ray detector launched by the National Aeronautics and Space Administration (NASA) in November 15, 1972. SAS-2 was Fichtel et al. (1975) 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 $\sim 115\,cm^2$. The spark chamber allowed for a seperate measurement of the electron and positron tracks, which allowd for improved directional reconstruction of the incident γ-ray. SAS-2 had a PSF $\sim 5°$ at 30 MeV and $\sim 1°$ 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 disovered strong emission along the Galactic plane and particularly towards the Galactic cente. It also discovered pulsations from the Crab (Fichtel et al. 1975) and Vela pulsar (Thompson et al. 1977b). In addition, SAS-2 discovered Geminga, the first γ-ray source with no compelling multiwavelenth counterpart (Thompson et al. 1977a). Gemina was eventually discovered to be a pulsar by the Energetic Gamma Ray Experiment Telescope (EGRET) (Bertsch et al. 1992) and retroactivly by SAS-2 (Mattox et al. 1992).

on August 9, 1975, the European Space Agency (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 calorimiter below the spark chamber which improved the energy resolution to $< 100\%$ for energies $\sim 3\,\mathrm{GeV}$ (Bignami et al. 1975). COS-B has a comparable effective area to SAS-2: $\sim 50\,\mathrm{cm}^2$ at $\sim 400\,\mathrm{MeV}$ (Bignami et al. 1975).

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 Mayer-Hasselwander et al. (1982). The second COS-B catalog (2CG) detailed the detection 25 γ-ray sources for $E > 100\,\mathrm{MeV}$ (Swanenburg et al. 1981). Figure 2.2 shows a map of these sources. Of these sources, the vast majority lay along the galactic plane and could not be positivly identified with sources observed at other wavelenths. In addition, COS-B observed the first ever extragalactic γ-ray source, (3C273, Swanenburg et al. 1978).

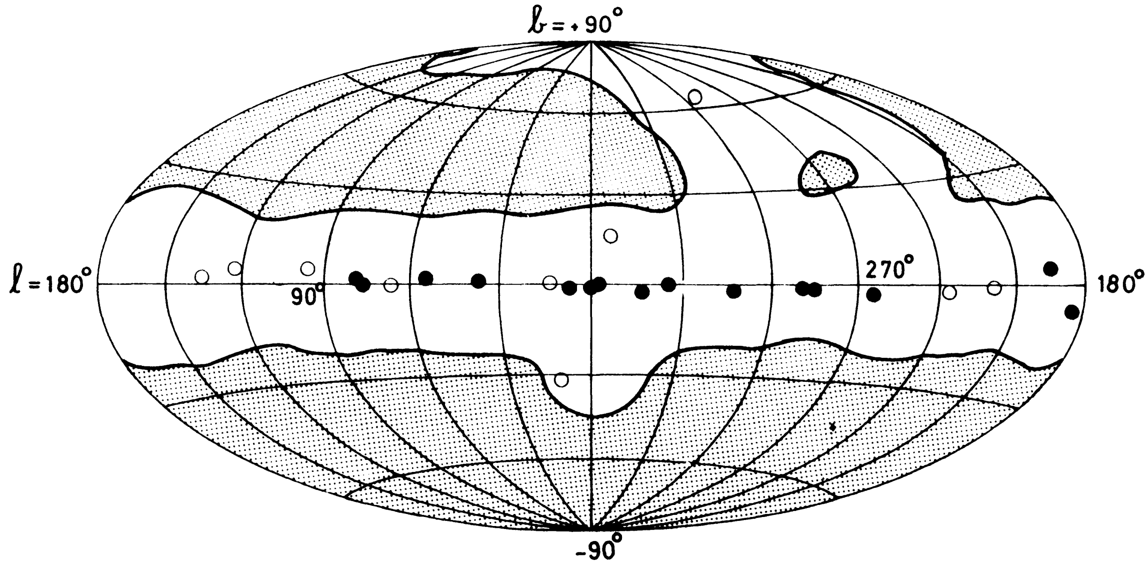

Figure 2.3: A map of the sources observed by COS-B. The filled circles represent brighter sources. The unshaded region corresponds to the parts of the sky observed by COS-B. This figure is from Swanenburg et al. (1981).

EGRET on board the Compton Gamma Ray Observatory (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*
- Short description of the history of TeV astronomy
- A detailed description of *Fermi* detector will be presented in Section 2.3.4.
- The major source classes detected by *Fermi* will be presented in Section 2.8

  The principles of the detector will be described in Section 2.3.4.

What is the LAT effective area?

2.3 The *Fermi* Gamma-ray Space Telescope

Large Area Telescope (LAT) is a pair-production telescope

2.3.1 The Tracker

2.3.2 The Calorimiter

2.3.3 Anti-Coincidence Detector

The Anti-Coincidence Detector (ACD) is . . .

2.3.4 Gamma-ray Burst Monitor

2.4 Astrophysical Sources of Gamma-rays

2.4.1 Pulsars

Pulsars were first discovered in 1967 by Jocelyn Bell Burnell and Antony Hewish (Hewish et al. 1968). They had constructed a radio telescope that used interplanetary scintillation wiht the intention of observing quasars. In the process, they detected a source with a periodicity of 1.3 s.

Make note of “Air force had early warning of pulsars” paper

Even before the discovery, Pacini (1967) had predicted the existence of neutron stars. Shortly following the 1967 discovery, Gold (1968) and Pacini (1968) argued that the observed pulsar was a rotating neutron star.

The discovery of many more pulsars came quickly. In 1968, and the Vela pulsar (Large et al. 1968) and the Crab pulsar (Staelin & Reifenstein 1968) were discovered.

The first pulsar observed at optical frequencies was the Crab, discovered in 1969 shortly after its radio discvoery (Cocke et al. 1969). 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 the Naval Research Laboratory (NRL) (Fritz et al. 1969) and at MIT (Bradt et al. 1969). 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.

- For Crab describe spin down?: "and these pulsations were then shown to be slowing down at a rate of 36 ns per day (Richards & Comella 1969)." – Gaensler & Slane (2006)

As was discussed in Section 2.2, γ-ray emission from the Crab was detected only 2 years later (Browning et al. 1971).

First gamma-ray detection

ATNF catalog?

- "There are currently more than 1,800 pulsars in the ATNF on-line catalog [Manchester et al., 2005], with rotation periods in the rage 0.0016-12 seconds (Figure 3.1) and derived spin down luminosities in the range XXX - XXX erg/s." – dalton_2011_identication-gamma-ray

EGRET pulsars?

The state of the art in γ-ray detection of pulsars will be included in an upcomming pulbication. 2PC: Section 2.8.2

When was the PSR, PWN connection made

2.4.2 Pulsar Wind Nebulae

A PWN is a diffuse nebula of shocked relativistic particles. A PWNs surrounds and is powered by an accompanying pulsar. PWNs have been observed long before the discovery of pulsars, but the pulsar/PWN connection could not be made until after the detection of pulsars.

The most famous PWNs is the Crab nebula, associated with the Crab pulsar.

- Chinese SN observations of Crab Nebulae: (p128 of "The Crab Nebula: An Astrophysical Chimera") "It was probably also recorded by Anasazi Indian artists (in present-day Arizona and New Mexico), as findings in Navaho Canyon and White Mesa (both Arizona) as well as in the Chaco Canyon National Park (New Mexico) indicate; there's a review of the research on the Chaco Canyon Anasazi art online. In addition, Ralph R. Robbins of the University of Texas has found Mimbres Indian art from New Mexico, possibly depicting the supernova." – http://messier.seds.org/m/m001.html

It was discovered in 1731 by physician and amateur astronomer John Bevis. This source was going to be published in his sky atlas *Uranographia Britannica*, but the work was never publisehd because his published filed for bankrupcy in 1950. Figure Figure 2.4.2 shows Beavis' plate containing the Crab nebula. A detailed history of John Bevis' work can be found in Ashworth (1981).

- Crab Nebulae is M1 in Charles Messier's catalog 1758 (p128 of "The Crab Nebula: An Astrophysical Chimera")

- Connection to 1054: "Lundmark (1921) suggested a connection between the Crab Nebula and the event of 1054 AD" (p128 of "The Crab Nebula: An Astrophysical Chimera") "The Crab Nebula (Fig. 1) is almost certainly associated with a supernova (SN) ex- plosion observed in 1054 CE (Stephenson & Green 2002, and references therein)." – "The Evolution and Structure of Pulsar Wind Nebulae" Bryan M. Gaensler and Patrick O. Slane

- "The same year, J.C. Duncan of Mt. Wilson Observatory compared photographic plates taken 11.5 years apart, and found that the Crab Nebula was expanding at an average of about 0.2" per year; backtracing of this motion showed that this expansion must have begun about 900 years ago (Duncan 1921). Also the same year, Knut Lundmark noted the proximity of the nebula to the 1054 supernova (Lundmark 1921)." – http://messier.seds.org/m/m001.html "In 1942, based on investigations with the 100-inch Hooker telescope on Mt. Wilson, Walter Baade computed a more acurate figure of 760 years age from the expansion, which yields a starting date around 1180 (Baade 1942); later investigations improved this value to about 1140. The actual 1054 occurrance of the supernova shows that the expansion must have been accelerated." – http://messier.seds.org/m/m001.html

- "but it was not until 1942 that Duyvendak (1942) and Mayall & Oort (1942) presented complete studies of modern observations of the expanding nebula and of the early Chinese records. It was this work that established unambiguously that the Crab is the remnant of SN1054." (p128 of "The Crab Nebula: An Astrophysical Chimera")

- "1949, the Crab nebula was identified as a strong source of radio radiation (Bolton et.al. 1949), discovered 1948 named and listed as Taurus A (Bolton 1948), and later as 3C 144." - http://messier.seds.org/m/m001.html

- Synchrotron emission hypotehsis: "while the inner, blueish nebula emits continuous light consisting of highly polarised so-called synchrotron radiation, which is emitted by high-energy (fast moving) electrons in a strong magnetic field. This explanation was first proposed by the Soviet astronomer J. Shklovsky (1953) and supported by observations of Jan H. Oort and T. Walraven (1956)." – http://messier.seds.org/m/m001.html

- "X-rays from this object were detected in April 1963 with a high-altitude rocket of type Aerobee with an X-ray detector developed at the Naval Research Laboratory; the X-ray source was named Taurus X-1. Measurements during lunar occultations of the Crab Nebula on July 5, 1964, and repeated in 1974 and 1975, demonstrated that the X-rays come from a region at least 2 arc minutes in size, and the energy emitted in X-rays by the Crab nebula is about 100 times more than that emitted in the visual light" – http://messier.seds.org/m/m001.html

- Association of Crab pulsar with Crab nebulae were discussed in (Staelin & Reifenstein 1968).

- TEV observations of Crab. brightest soruce in the sky...

- Now many radio, x-ray PWNe. Count form PWN catalog: http://www.physics.mcgill.ca/ pulsar/pwncat.html “Observations over the last several decades have identified 40 to 50 further sources, in both our own Galaxy and in the Magellanic Clouds, with properties similar to those of the Crab Nebula (Green 2004; Kaspi, Roberts & Harding 2006)” – Gaensler & Slane (2006)

- How many TeV PWNe in TeVCat? http://tevcat.uchicago.edu/ (31 by my preliminary count)

2.5 Radiation Processes in Gamma-ray Astrophysics

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

2.5.1 Synchrotron

2.5.2 Inverse Compoton

IC emission is . . .

IC

2.5.3 Bremsstrahlung

2.5.4 Pi0 Decay

2.6 The Pulsar/Pulsar Wind Nebulae System

Describe pulsar/PWN/SNR system:

- Describe how a supernova creates an SNR and leaves behinda a pulsar wind nebula.

- “Pulsars are now known to be created in Supernova events, where the dense stellar core created in thermonuclear reactions is left over after the nova event. Depending on its mass, the remaining solar core may form a neutron star or a black hole. The determining criterion is the Chandrasekhar limit (MCh) given by:" – dalton_2011_identication-gamma-ray

2.6.1 Pulsar Properties

XXXXXXXXXXXXXXXX

- "Following this discovery, a theoretical understanding was soon developed in which the central pulsar generates a magnetized particle wind, whose ultrarelativistic electrons and positrons radiate synchrotron emission across the electromagnetic spectrum (Pacini & Salvati 1973, Rees & Gunn 1974). The pulsar has steadily released about a third of its total reservoir of ???? ergs of rotational energy into its surrounding nebula over the last 950 years. This is in sharp contrast to shell-like SNRs, in which the dominant energy source is the ??? ergs of kinetic energy released at the moment of the original SN explosion." – Gaensler & Slane (2006)
- What is terminaltion shock of PWNe.
- How is pulsar outflow accelerated at shock?

Find a plot of a rotating pulsar. The simplest rotating dipole model

The energy powering pulsars and PWNs is comonly believed to originate in rotational kintetic energy stored in the netutron star. Both the period P and the period derivative $\dot{P} = dP/dt$ can be directly observed for a pulsar and typically the pulsar is slowing down ($\dot{P}$ ¡0). We write the rotational kinetic energy as

$$E_{\rm rot} = \tfrac{1}{2} I \Omega^2 \tag{2.1}$$

where $\omega = 2\pi/P$ and P is the period of rotation of the pulsar. We make the conection between the pulsar's spin-down energy and the rotational kintecit energy as $\dot{E} = -\mathrm{d}E_{\rm rot}/\mathrm{d}t$

The rotational kinetic energy in a pulsar can be written as

$$\dot{E} = 4\pi^2 I\dot{P}/P^2, \tag{2.2}$$

where I is the moment of inertia. For a uniform sphwere,

$$I = \frac{2}{5}MR^2 \tag{2.3}$$

Pulsars are assumed to be uniform spheres with $R = 10\,\mathrm{km}$ and $M = 1.4M_\odot$, which leads to a canonical moment of inertia of $I = 10^{45}\,\mathrm{gcm}^{-2}$.

It is believed that as the pulsar spins down, the this rotational energy is released as pulsed electromagnetic radiation and also as a wind of electrons and positrons accelerated in the magnetic field of the pulsar.

As the pulsar slows down, it released the rotational kinetic energy

$$\dot{E} = -\frac{4\pi^2 I\dot{P}}{P^3} \tag{2.4}$$

where $\dot{P}$ is the rate of decrease in the period of the pulsar.

Discuss uniform dipole model

We conventionally assume that the period and period derivative are related by the equation

$$\dot{\Omega} \propto \Omega^n \tag{2.5}$$

where $\Omega = 2\pi/P$, and n is the pulsar breaking index.

- "though n has only been confidently measured for five pulsars, in each case falling in the range 2 ¡ n ¡ 3 (Livingstone et al. (2007) and references therein)." – Adam Van Etten's thesis

- "The braking index is the power to which the slowdown in angular velocity occurs, and is defined as:

$$n = \frac{P\ddot{P}}{\dot{P}} + 2 \tag{2.6}$$

" – keogh_2010_search-pulsar

Equation Equation 2.5 is a Bernoulli differential equation which can be integrated to solve for time

$$T = \frac{P}{(n-1)|\dot{P}|}\left(1 - \left(\frac{P_0}{P}\right)^{(n-1)}\right) \tag{2.7}$$

- TODO: cite Manchester & Taylor 1977

$$\tau_c = P/2\dot{P} \tag{2.8}$$

- What is a typical moment of inertia, typical dE/dT
- What fraction of pulsar energy is released observationally

2.6.2 Pulsar Magnetosphere

2.6.3 Pulsar Wind Nebulae

- Discuss termination shock (i.e. section 3.3.2 of dalton_2011_identication-gamma-ray
- The radius of the termination shock is

$$r_{\text{ts}} = \sqrt{\frac{\dot{E}}{\frac{4}{3}\pi P_{\text{ISM}} c}} \tag{2.9}$$

Discuss pulsar evolution “The Evolution and Structure of Pulsar Wind Nebulae” – Bryan M. Gaensler and Patrick O. Slane

Describe Mattana’s work on PWNe: “On the evolution of the Gamma- and X-ray luminosities of Pulsar Wind Nebulae”

2.7 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 2.2.

- 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

2.8 Sources Detected by the Fermi Large Area Telescope

- A variety of sources detected by the Large Area Telescope:

2.8.1 The second *Fermi* catalog

The second *Fermi* catalog (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 LAT
- Forward reference Chapter 3, which does a more thorough description of likelihood analysis method.
- Source classes/associations

2.8.2 The second *Fermi* pulsar catalog

The second *Fermi* pulsar catalog (2PC) is a ...

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

2.8.3 Pulsar wind nebula Detected by the Large Area Telescope

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: Aharonian et al. (2006a)

LAT Detection: Grondin et al. (2011)

HESS J1640−465

HESS J1640−465 is also cool.

HESS detection: Aharonian et al. (2006b) Fermi detection: Slane et al. (2010)

2FGL J1857+026

2FGL J1857+026 is another good source.

LAT detection: Rousseau et al. (2012)

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

J1023

...

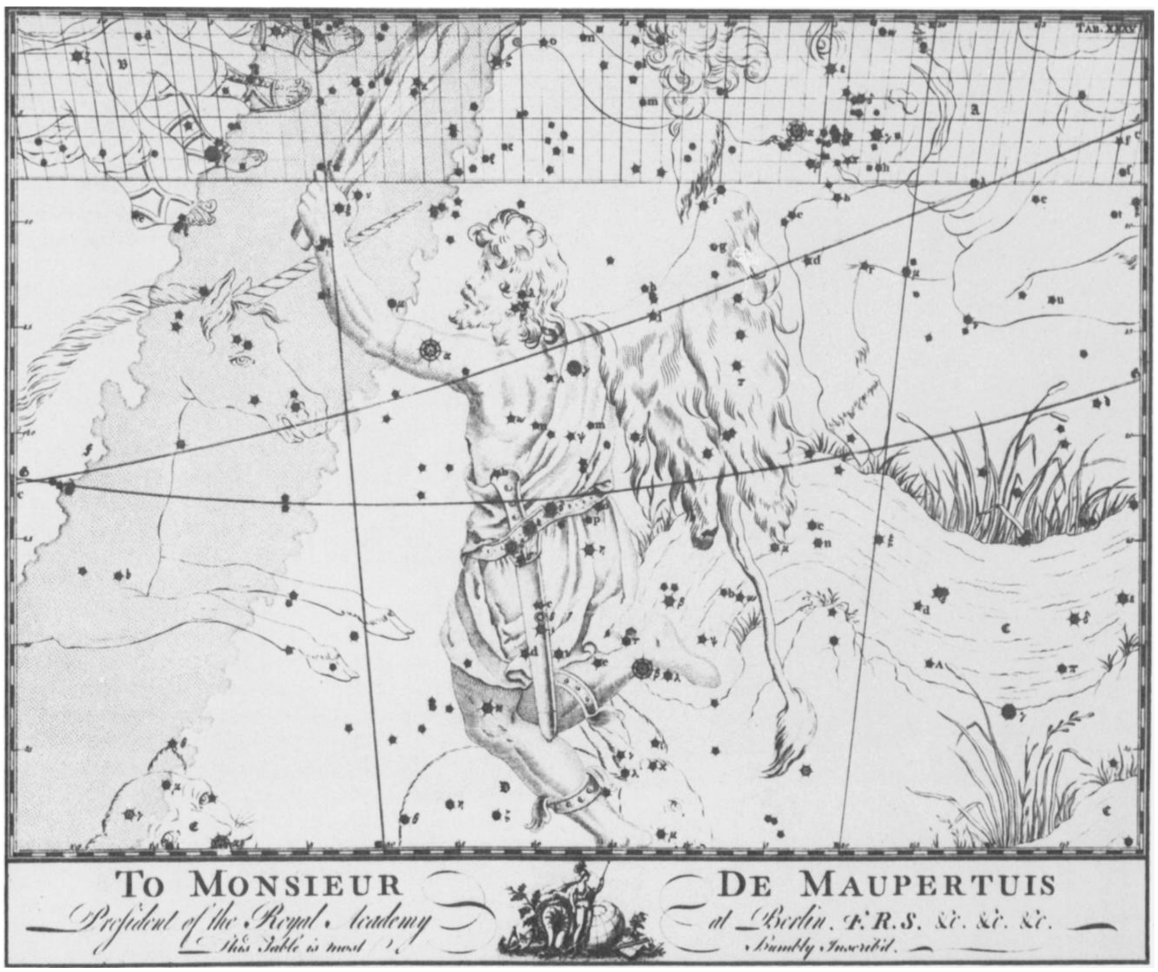

Figure 2.4: The Orion plate from Bevis' book *Uranographia Britannica*. The Crab nebula can be found on the horn of Taurus the Bull on the top of the figure and the source is marked by a cloudy symbol. This figure was reproduced from Ashworth (1981).

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 invovled 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` pacakge, an alterate 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 not that much of the notation and formulation of likelihood analysis in this chapter follows Kerr (2010).

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

Traditonally, 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 telesocpe'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 Poission 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 istropic so that the background level below the source can be estimated from nearby regions. As was discussed in Section 2.7, the Galactic diffuse emission is highly anistropic, 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 $\sim 5°$. But within the inner $45°$ of the galactic plane in longitude and $0.5°$ of the galactic plane in latitidue, there are 73 sources, corresponding to a source density of ~ 1 source per square degree. The aperature photometry method is unable to effecitvly 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 ($\gtrsim 1°$) at low energy and much narrower ($\sim 0.1°$) at higher energies. Therefore,

what section discusses energy

there is a much higher sensitivty 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 Analaysis

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 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 devoped 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:

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

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

Generaly, 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:

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

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 Therorem and it's 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 the Centimetre-Gram-Second System of Units (CGS), it has units of ph cm^{-2}s^{-1}erg^{-1}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

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

Here, $\frac{dN}{dE}$ is only a function of energy and 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 PDF$(\vec{\Omega})$ function. In CGS, $\frac{dN}{dE}$ is in units of ph cm^{-2}s^{-1}erg^{-1}.

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

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

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 broken-power law (BPL) spectral model

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

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 exponentially-cutoff power law (ECPL) spectral model is often used to model the γ-ray emission from pulsars:

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

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 emisison. It is traditionally normalized as though it was a probability:

$$\int d\Omega\ \mathrm{PDF}(\vec{\Omega}). \tag{3.7}$$

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

$$\mathrm{PDF}(\vec{\Omega}) = \delta(\vec{\Omega} - \vec{\Omega}') \tag{3.8}$$

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

WHAT SECTION DESCRIBES EXTENDED SOURCE PDFs

This formulation assumed that the source models are not time dependent. This is traditionally because it is difficult to find simple paremterized models to fit the time behavior of a variable source. Instead, the typtical strategy to fit varaible 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 supernova remnants (SNRs) which could show a spectral variation across the source. Katsuta et al. (2012) and Hewitt et al. (2012) have simplied this problem by A simple method which has been adopted to study this kind of sourcc.

FINISH DISCUSSION

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 and requires a mapcube.

3.4 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

$$\int\int\int \mathrm{d}E d\Omega \mathrm{d}t P(E',t',\vec{\Omega}'|E,t,\vec{\Omega}) = 1 \tag{3.9}$$

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

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

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':

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

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:

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

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

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

$\mathrm{E_{disp}}$ 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 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:

$$\mathrm{E_{disp}} = \delta(E - E') \tag{3.13}$$

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.

- $\mathrm{T_{disp}}$ 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 FINISH

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

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:

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

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 depedence of the IRFs factors into this calcualtion

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-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

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

  - 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 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:

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

  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:

$$\theta_j = \sum_i \theta_{ij} \tag{3.18}$$

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

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

3.6 The Alternate Maximum-Likelihood Package `pointlike`

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

Chapter 4

Analysis of Spatially Extended LAT Sources

This chapter is based the first part of the the paper “Search for Spatially Extended Fermi-LAT Sources Using Two Years of Data” by Lande et at al. 2012 ApJ, 756, 5

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

This chapter is based the second part of the the paper "Search for Spatially Extended Fermi-LAT Sources Using Two Years of Data" by Lande et at al. 2012 ApJ, 756, 5

5.1 Extended Source Search Method

5.2 New Extended Sources

5.3 Discussion

Chapter 6

Search for Pulsar wind nebula (PWN) associated with Gamma-loud Pulsars

This chapter is basd on work from 2PC. GET REFERENCE HERE.

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 Pulsar wind nebula (PWN) 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 Pulsar Wind Nebulae associated with High $\dot{E}$ Pulsars

Chapter 9

Population Study of Large Area Telescope (LAT)-detected Pulsar wind nebula (PWN)

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

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