# Todo list

# OBSERVATIONS OF PWNE WITH THE FERMI GAMMA-RAY SPACE TELESCOPE

A DISSERTATION
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DOCTOR OF PHILOSOPHY

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

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Approved for the University Committee on Graduate Studies

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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

**2CG** The Second COS-B catalog

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

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

**PL** power law

**ECPL** exponentially-cutoff power law

**BPL** broken-power law

**MIT** Massachusetts Institute of Technology

**OSO-3** the Third Orbiting Solar Observatory

**SAS-2** the second Small Astronomy Satellite

**EGRET** the Energetic Gamma Ray Experiment Telescope

**CGRO** the Compton Gamma Ray Observatory

**ESA** the European Space Agency

**NASA** the National Aeronautics and Space Administration

**NRL** the Naval Research Laboratory

# Chapter 2

# Gamma-ray Astrophysics

## 2.1 The History of Gamma-ray Astrophysics

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. Slowly, over time, astronomers expanded their view across the electromagnetic spectrum.

Infrared radiation from the sun was first observed by William Herschel in 1980 (Herschel 1800). The first extraterrestrial source of radio waves was detected by Jansky in 1933 (Jansky 1933).

The development of rockets and sattelites in the 20th ceuntry allowed the field of astronomy to expand futher, allowering observations at wavelengths that would otherwise be absorbed in the atmosphere. 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)

It was only natural to wonder about the universe at even higher energies. As is common in the field of physics, the prediction of the detection of cosmic $\gamma$-rays far proceded their discovery. Feenberg & Primakoff (1948) theorized that the interaction of starlight with cosmic rays could produce $\gamma$-rays through Inverse Compoton (IC) upscattering. Following the discovery of the neutral pion in 1949, Hayakawa (1952) predicted that $\gamma$-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 $\gamma$-rays including solar flares, Pulsar Wind Nebulae (PWNe), and active galaxies.

Why Gamma-rays can't make it to the ground

Discuss Balloon gamma-ray detectors. See discussion on p859 (comparison with other experiments) of Kraushaar et al 1965. What was the background from, earth albedo gammas I think? See also Kraushaar et al 1972 p342's discussion of the balloon experiments: Hulsizer and Rossi (1949), ... See also William Tomkin's section 2.2.1 on Balloon experiments (page 8) for references to galactic plane emission being measured by balloon experiments in 1970.

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 $\gamma$-rays was hampered by the strong background of atmospheric albedo $\gamma$-rays.

The first space-based $\gamma$-ray detector was Explorer XI Kraushaar et al. (1965). It was developed at 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 $\gamma$-rays and was surounded by a plastic anticoincidence scintilation counter. The sandwich detector had an area of $\sim 45\text{cm}^2$, but an effective area of only $\sim 7\text{cm}^2$, corresonding to a detector efficiency of $\sim 15\%$.

What was the energy range of explorer ii

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 $\gamma$-rays and, because the distribution a distribution of these $\gamma$-rays was consistent with being isotropic, the experiment could not firmly identify the $\gamma$-rays as being cosmic in nature.

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

The first definitive detection of $\gamma$-ray came in 1962 by an experiment on the Ranger 3 moon probe (Arnold et al. 1962). It detected an isotropic flux of $\gamma$-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 $\gamma$-ray detector Kraushaar et al. (1972). The OSO-3 sattelite allowed the on board $\gamma$-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 and had an effective area $\sim 9$ cm$^2$.

It was launched on March 8, 1967 and operated for 16 months, measuring 621 cosmic $\gamma$-rays. The most important result of the expirment was to measure a strong anisotrophy in the distribution of the $\gamma$-rays with a strong clustering of $\gamma$-rays towards the Galactic plane. Figure 2.1 shows a skymap of these $\gamma$-rays. This experiment confirmed both a Galactic component to the $\gamma$-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?

Concurently with the major adavnces in space-based $\gamma$-ray detects came improved balloon-based $\gamma$-ray detectors.

Discuss Kniffen & Fichtel (1970) and Browning et al. (1971). Do a literature seach to see if there are other balloon experiments which detected similar stuff.

The next major advancement in $\gamma$-ray astronomy came from the the second Small Astronomy Satellite (SAS-2) and COS-B missions.

SAS-2 was a dedicated $\gamma$-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 $\gamma$-ray. SAS-2 had a PSF $\sim 5°$ at 30 MeV

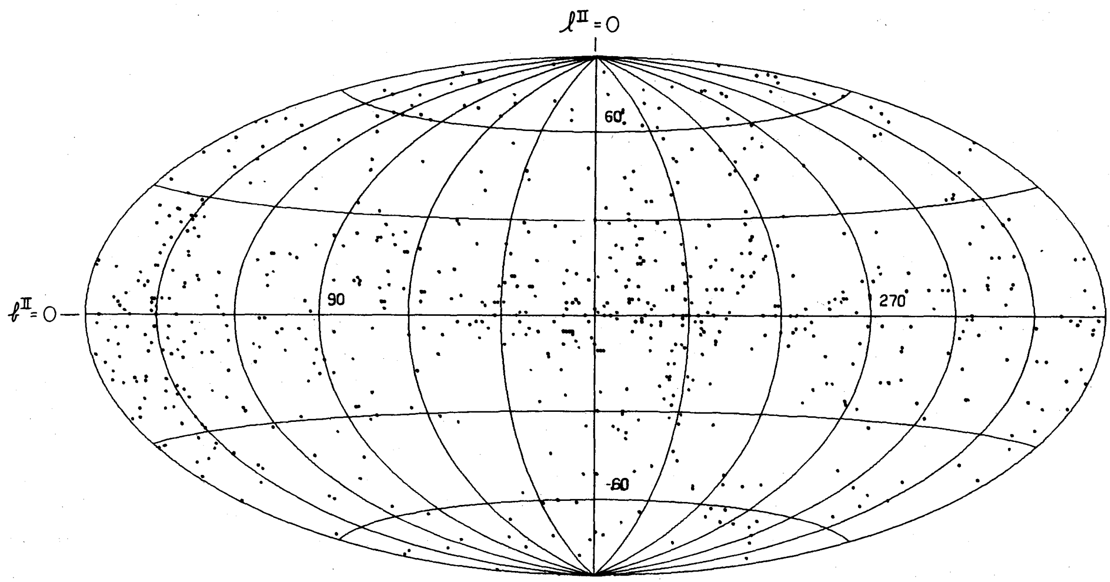


Figure 2.1: The position of all 621 cosmic $\gamma$-rays detected by OSO-3. This figure is from Kraushaar et al. (1972).

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 $\gamma$-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 $\gamma$-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 $\gamma$-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 $\gamma$-ray sky. In total, COS-B observed $\sim 80,000$ photons **?**. The Second COS-B catalog (2CG) detailed the detection 25 $\gamma$-ray sources for $E > 100\,\mathrm{MeV}$ (Swanenburg et al. 1981). Figure 2.1 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 $\gamma$-ray source, (3C273, Swanenburg et al. 1978).

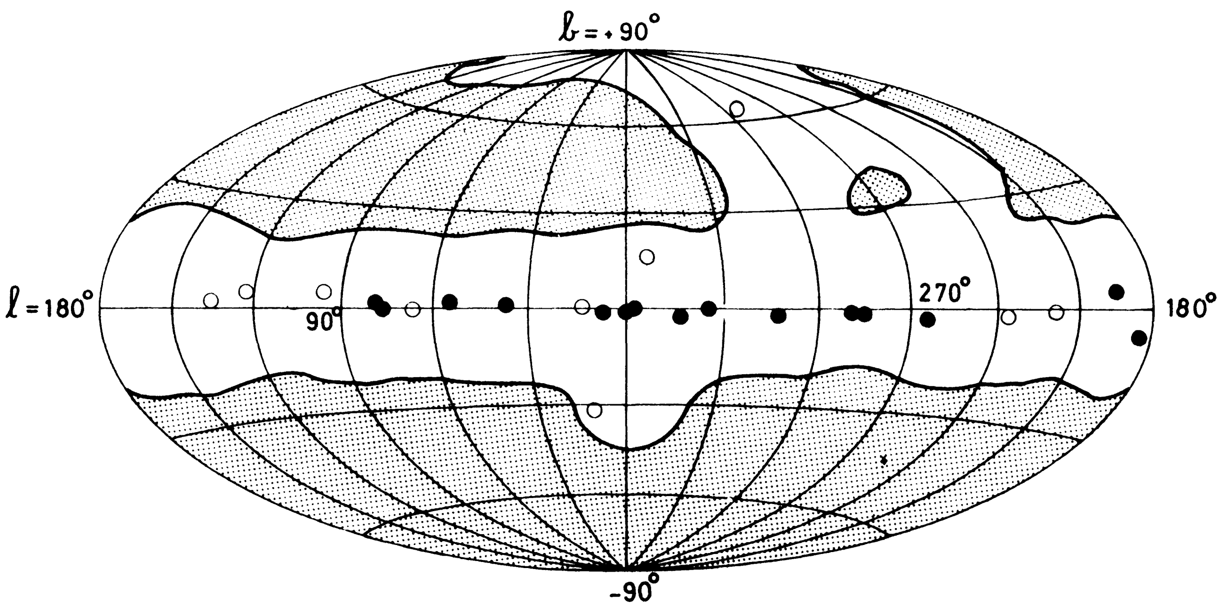


Figure 2.2: A map of the sources observed by COS-B. The filled circles represent brighter sources. The unshaded region corresponds to the parts of the sky observed by COS-B. This figure is from Swanenburg et al. (1981).

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 $\gamma$-rays EGRET detect?

How many pulsars did EGRET detect?

- AGILE
- *Fermi*
- Short description of the history of TeV astronomy

## 2.2 Astrophysical Sources of Gamma-ray

### 2.2.1 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.

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.

WHen was crab discovdered? WHat about ohter discovderies

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!** (**mit!**) (Bradt et al. 1969). and

ATNF catalog?

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

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

$$\tau_c = P/2\dot{P} \tag{2.2}$$

### 2.2.2 Pulsar Wind Nebulae

### 2.2.3 Supernova Remenants

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

## 2.4 Radiation Processes in Gamma-ray Astrophysics

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

### 2.4.1 Synchrotron

### 2.4.2 Inverse Compoton

IC emission is ...

### 2.4.3 Bremsstrahlung

### 2.4.4 Pi0 Decay

## 2.5 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 2.1.

- 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

## 2.6 Sources Detected by the Fermi LAT

- A variety of sources detected by the LAT:

### 2.6.1 The Second *Fermi*-LAT catalog (2FGL)

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

Describe Catalog

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

### 2.6.2 The Second Fermi Pulsar Catalog

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

### 2.6.3 PWNe Detected by the LAT

#### Crab

#### Vela X

#### MSH 15-52

#### 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

. . .

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