

# Abstract

Title of Dissertation:  $\gamma$ -Ray Studies of Stellar Graveyards:  
Observations of Extended Emission from  
Supernova Remnants and Pulsar Wind Nebulae.

Jamie Michael Cohen, Doctor of Philosophy, 2016

Dissertation directed by: Doctor Elizabeth Hays  
Astroparticle Physics Laboratory, Code 661  
NASA Goddard Space Flight Center

Professor M. Coleman Miller  
Department of Astronomy  
University of Maryland

Here I shall abstract!

**$\gamma$ -Ray Studies of Stellar Graveyards:  
Observations of Extended Emission from  
Supernova Remnants and Pulsar Wind Nebulae.**

by

Jamie Michael Cohen

Dissertation submitted to the Faculty of the Graduate School of the  
University of Maryland at College Park in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy  
2016

Advisory Committee:

Doctor Elizabeth Hays, Advisor  
Professor M. Coleman Miller, Chair/Advisor  
Professor Christopher S. Reynolds  
Professor Derek C. Richardson  
Doctor Who

© Jamie Michael Cohen 2016

# Preface

Brief description of the content of this thesis. Statements about which chapters (or parts of) have been published where. Reference like Part of Chapter 1

To Vanessa!

# Acknowledgements

I should probably thank someone.

# Contents

List of Tables	vi
List of Figures	vii
<b>1 Introduction</b>	<b>1</b>
1.1 Gooooo $\gamma$ -rays go! . . . . .	1
1.2 Dissertation Overview . . . . .	1
<b>2 Gamma-ray Astronomy</b>	<b>2</b>
<b>3 The Fermi Gamma Ray Space Telescope</b>	<b>3</b>
3.1 Overview . . . . .	3
3.2 The Large Area Telescope . . . . .	3
<b>4 Stellar Remnants</b>	<b>5</b>
4.1 Introduction . . . . .	5
4.2 Supernova Remnants . . . . .	5
4.3 Pulsar Wind Nebulae . . . . .	6
4.4 Summary . . . . .	6
<b>5 The 1<sup>st</sup> <i>Fermi</i>-LAT Supernova Remnant Catalog</b>	<b>7</b>
5.1 Input Source Model Construction . . . . .	7
5.2 Comparison of Source Models with 2FGL . . . . .	12
5.3 Summary . . . . .	15
<b>6 Extended Source Detection above 50 GeV: The 2FHL Catalog</b>	<b>16</b>
6.1 Extended Sources Previously Detected by the LAT . . . . .	17
6.2 Newly Detected Extended Sources . . . . .	17
6.3 Extended Source Results . . . . .	19
6.4 Summary . . . . .	22

<b>7</b>	<b>SNR G150.3+4.5</b>	<b>25</b>
7.1	Summary . . . . .	25
7.2	Introduction . . . . .	26
7.3	<i>Fermi</i> LAT Observations and Analysis . . . . .	26
7.3.1	Data Set and Reduction . . . . .	26
7.3.2	Morphological Analysis . . . . .	28
7.3.3	Spectral Analysis . . . . .	33
7.4	Multiwavelength Observations and Analysis . . . . .	33
7.4.1	HI . . . . .	33
7.4.2	CO? . . . . .	33
7.4.3	X-ray . . . . .	34
7.5	Discussion and Results . . . . .	35
7.5.1	What is it? . . . . .	35
7.5.2	Distance Considerations . . . . .	36
7.5.3	Nonthermal Modeling . . . . .	37
7.6	Conclusions . . . . .	37
<b>8</b>	<b>SNR-MC, 10 GeV, and anything else?</b>	<b>38</b>
<b>9</b>	<b>Conclusions</b>	<b>39</b>
	<b>List of Symbols and Acronyms</b>	<b>40</b>
	<b>Bibliography</b>	<b>41</b>



# List of Tables

6.1	2FHL extended sources previously detected by the <i>Fermi</i> -LAT . . . .	23
6.2	New 2FHL extended sources . . . . .	23
7.2	New 2FHL extended sources . . . . .	32

# List of Figures

5.1	Comparison of the number of 2FGL sources with $TS_{1-100\text{ GeV}} \geq 25$ (excluding AGN and pulsars) with the number of newly added input model sources in the present analysis, for sources within $3^\circ$ of the center of each RoI. The color scale shows the number of RoIs with a particular combination of numbers of 2FGL sources and new sources. White corresponds to no RoI with that combination of source counts.	14
5.2	Same as Figure 5.1, including only input model sources lying within $0.2^\circ$ of a 2FGL source. . . . .	15
6.1	TS maps for the five new extended sources described in § 6.3. Only the Galactic diffuse and isotropic emission are included in the model to highlight the location of emission not associated with the diffuse background. Circles indicate the extents of the fit disks. The x marker in the bottom panel (2FHL J0431.2+5553e) shows the location of a point source in the ROI. . . . .	24
7.1	Background subtracted residual TS map above 1 GeV with $0.1^\circ \times 0.1^\circ$ pixels for fixed index $\Gamma = 2$ , centered on SNR SNR G150.3+4.5. The orange circle and translucent shading show the fit disk radius and $1\sigma$ errors, respectively, for the extended source, the orange cross shows the position of 3FGL J0426.7+5437 (included in the background model), and blue dashed circle is the extent of the radio SNR. . . . .	30
7.2	Same as Figure 7.1 but with disk in the background model [JAM: should this be a residual counts map instead?] . . . . .	31
7.3	Spectral energy distribution for the extended source coincident with SNR SNR G150.3+4.5. [JAM: replace with gtlike SED when I have it]	34
7.4	Spectral energy distribution of 3FGL J0426.. [JAM: replace with gtlike SED when I have it] . . . . .	35

# Chapter 1

## Introduction

“Maybe I’ll have a super relevant quote here!”

—by some awesome human, from *Some book*

### 1.1 Goooo $\gamma$ -rays go!

In this thesis we...or should I start with the extreme environs line?

Overview of the entire thesis, why gamma-rays, why the Large Area Telescope (LAT), why supernova remnant (SNR) and pulsar wind nebula (PWN) and extended sources.

### 1.2 Dissertation Overview

# Chapter 2

## Gamma-ray Astronomy

The story of  $\gamma$ -ray's from astrophysical objects is a tale of the most extreme, energetic, and violent environments in our universe. Discovered by Paul Villard studying radiation from radium and named by Ernest Rutherford, who previously uncovered the nature of  $\alpha$  and  $\beta$  radiation,

accelerator plus target often gamma-rays, gamma-ray astronomy, gamma-ray sky, connection to CR

gamma-ray production mechanisms

gamma-ray astronomy is really a proxy for studying cosmic rays and acceleration/diffusion processes. How much to get into CR.

gamma-ray telescopes leads into the LAT, Egret was predecessor , what it did and what were some relevant unanswered questions regarding supernova remnants

Maybe combine the telescope stuff with the LAT section and leave this section for history and astrophysics of  $\gamma$ -rays? Or just combine this section with LAT section?

Altho' many miles from bomb zero, Dr. Bruce Banner is bathed in the full force of the mysterious Gamma Rays!

# Chapter 3

## The Fermi Gamma Ray Space Telescope

### 3.1 Overview

General info about Fermi, when it was conceived, launched, what questions it was designed to address etc.

### 3.2 The Large Area Telescope

Details on the LAT and its design, be sure to focus on things that particularly pertain to the work I've done like what determines the PSF, thing about Pass 8 here maybe? Or maybe later on.

what science was it designed to answer

general capabilities

details about aspect of the LAT related to extended sources, what determines PSF

Searching for extended Galactic sources leads into stellar remnants section?

Merged this with the LAT analysis section

I'm not sure about this chapter yet. Maybe it's a general section on Analysis of Fermi data, why maximum likelihood, how it's formulated, implemented in the Science Tools, pointlike and the analysis for extended sources. Diffuse emission

Four steps to going from observing the sky to final LAT analysis:

Instrument taking data: How we get to counts

Reconstruction : How we get photons

Likelihood: How to characterize sky using response functions, point source and diffuse modeling

Likelihood for ES: how to use likelihood methods to char and resolve sources  
measure extension

# Chapter 4

## Stellar Remnants

Is it weird to call them stellar remnants? It's not like the remnant of the star, but of the supernova. Gamma ray sources this thesis focuses on

### 4.1 Introduction

Brief history of radio detection of SNRs. detection at other wavelengths. what we see at  $\gamma$ -rays?

### 4.2 Supernova Remnants

History of SNR, radio detections, then x-ray, can't really ID in new ones with the LAT, theory: snow plow , ST evolution, radiative phase, shell type, mixed morphology (shell plus center filled thermal x-ray)

## 4.3 Pulsar Wind Nebulae

How much of my thesis is really about pwn? in 2FHL we detect some. if including above 10gev work, they'll be there too. Much of the thesis is really about extended gamma-ray sources, but not sure how that fits into the title and chapters yet

Do I need to get into composite SNRs (I think composite means SNR + PWN right?) Maybe relevant for G150? Some things about interaction of reverse shock with PWN and crushing/reverberations of the PWN?

How we detect gamma-rays from SNRs/PWNe in the Galaxy leads to an analysis section maybe?

## 4.4 Summary

In this section we summarized the end phase of stellar evolution (just enough to motivate SNRs) and described the environs surrounding the supernova; development and phases of SNRs (and PWNe?). In particular we detailed the nonthermal emission mechanisms that produce  $\gamma$ -ray radiation, detection of young vs middle-aged (evolved, interacting with surroundings/dense medium), TeV detects younger typically, the troubles of detecting extension from them(?) something about different emission zones? Troubles disentangling hadronic from leptonic at  $\gamma$ -rays.  $\gamma$ -ray spectral and morphological features. Trends across the population wrt spectral shape/breaks, higher luminosity for interacting remnants. Cosmic rays, using gamma-rays to probe CR population. So much of  $\gamma$ -ray astro is really about studying CRs, how much to say about them?



# Chapter 5

## The 1<sup>st</sup> *Fermi*-LAT Supernova Remnant Catalog

[JAM: Change chapter title to reflect the work I've done more]

How much of the First Fermi-LAT supernova remnant catalog (SNRcat) paper can I put in as is, how much can I take with modifications? Below is just the addSrcs section and appendix A

[JAM: Refs from snr cat paper aren't working yet]

### 5.1 Input Source Model Construction

To characterize each candidate SNR we constructed a model of  $\gamma$ -ray emission in the RoI which includes all significant sources of emission as well as the residual background from CRs misclassified as  $\gamma$ -rays. We implemented an analysis method to create and optimize the [JAM: fill this in ] models for each of the 279 RoIs. For each RoI, we started with all sources listed in the Second Fermi LAT source catalog (2FGL) (?), based on 2 years of Source class data, within the RoI. To this we add pulsars from Second Fermi LAT catalog of Gamma-ray Pulsars (2PC) (?), based on

3 years of source class data, with 2PC taking precedence for sources that exist in both. For the diffuse emission we combined the standard IEM corresponding to our P7 data set, `gal_2yearp7v6_v0.fits`, with the standard model for isotropic emission, which accounts for extragalactic diffuse  $\gamma$ -ray emission and residual charged particles misclassified as  $\gamma$ -rays. Both the corresponding isotropic model, `iso_p7v6source.txt`, and the IEM are the same as used for the 2FGL catalog analysis<sup>1</sup>.

Compared to 2FGL, we used an additional year of data and limited the energy range to  $1 - 100$  GeV. This can result in different detection significances and localizations than previously reported in 2FGL. To account for these effects, we recreated the RoIs' inner  $3^\circ$  radius regions, which encompass the radio extents of all known SNRs, observed to be  $\leq 2.6^\circ$  and allows a margin for the LAT PSF. The weighted average 68% containment radius of the LAT PSF for events at 1 GeV is  $\sim 0.7^\circ$  (?). We note that this implicitly assumes that an SNR's GeV extent should not be more than about an order of magnitude larger than its radio extension and also note that the selection biases stated in Green's catalog limit the range of known SNRs' radio extensions.

To build the inner  $3^\circ$  radius model of each RoI, we first removed all sources except identified Active Galactic Nuclei (AGN) and pulsars, whose positions on the sky are independently confirmed by precise timing measurements (?). Retained AGN were assigned their 2FGL positions and spectral model forms. Pulsars' positions and spectral forms were taken from 2PC. 2FGL sources identified or associated with SNRs are removed when they lie within the inner  $3^\circ$ .

We generated a map of source test statistic (TS) defined in ? via `pointlike` on a square grid with  $0.1^\circ \times 0.1^\circ$  spacing that covers the entire RoI. `pointlike`

---

<sup>1</sup>Further details on the diffuse emission models are available at <http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

employs a binned maximum likelihood method. The source TS is defined as twice the logarithm of the ratio between the likelihood  $\mathcal{L}_1$ , here obtained by fitting the model to the data including a test source, and the likelihood  $\mathcal{L}_0$ , obtained here by fitting without the source, i.e.,  $\text{TS} = 2 \log(\mathcal{L}_1/\mathcal{L}_0)$ . At the position of the maximum TS value, we added a new point source with a Power Law (PL) spectral model:

$$\frac{dN}{dE} = N \frac{(-\Gamma + 1)E^{-\Gamma}}{E_{\text{max}}^{-\Gamma+1} - E_{\text{min}}^{-\Gamma+1}} \quad (5.1)$$

where  $N$  is the integrated photon flux,  $\Gamma$  is the photon index, and  $E_{\text{min}}$  and  $E_{\text{max}}$  are the lower and upper limit of the energy range in the fit, set to 1 GeV and 100 GeV, respectively. We then performed a maximum likelihood fit of the RoI to determine  $N$  and  $\Gamma$  and localized the newly added source. The significance of a point source with a PL spectral model is determined by the  $\chi_n^2$  distribution for  $n$  additional degrees of freedom for the additional point source, which is typically slightly less than  $\sqrt{\text{TS}^2}$ .

To promote consistent convergence of the likelihood fit, we limited the number of free parameters in the model. For sources remaining after the removal step, described above, we freed the normalization parameters for the sources within  $5^\circ$  of the RoI center, including identified AGN and pulsars. For 2FGL sources between  $5^\circ$  and  $10^\circ$ , we fixed all parameters. The spectrum of the IEM was scaled with a PL whose normalization and index were free, as done in 2FGL. For the isotropic emission model, we left the normalization fixed to the global fit value since the RoIs are too small to allow fitting the isotropic and Galactic IEM components independently. The isotropic component's contribution to the total flux is small compared to the IEM's at low Galactic latitudes.

After localizing them, the new sources were tested for spectral curvature. In each

---

<sup>2</sup>See [http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone\\_Likelihood/TS\\_Maps.html](http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood/TS_Maps.html) for further details.

of the 4 energy bands per decade we calculated the TS value for a PL with spectral index fixed to 2 and then summed the TS values. We refer to this as  $\text{TS}_{\text{bandfits}}$ . A value for  $\text{TS}_{\text{bandfits}}$  much greater than the TS calculated with a PL ( $\text{TS}_{\text{PL}}$ ) suggests with a more rapid calculation that the PL model may not accurately describe the source. Analogously to 2FGL (?), we allow for deviations of source spectra from a PL form by modeling sources with a log-normal model known colloquially as LogParabola or logP:

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_b} \right)^{-(\alpha + \beta \log(E/E_b))} \quad (5.2)$$

where  $N_0$  is the normalization in units of photons/MeV,  $\alpha$  and  $\beta$  define the curved spectrum, and  $E_b$  is fixed to 2 GeV. If  $\text{TS}_{\text{bandfits}} - \text{TS}_{\text{PL}} \geq 25$ , we replaced the PL spectral model with a logP model and refit the RoI, including a new localization step for the source. We retained the logP model for the source if the global  $\log \mathcal{L}$  across the full band improved sufficiently:  $\text{TS}_{\text{curve}} \equiv 2(\log \mathcal{L}_{\text{logP}} - \log \mathcal{L}_{\text{PL}}) \geq 16$ . Otherwise we returned the source to the PL model which provided the better global  $\log \mathcal{L}$ . Across all RoIs, less than 2% of the newly added sources retained the logP model.

We continued iteratively generating TS maps and adding sources within the entire RoI until additional new sources did not significantly change the global likelihood of the fit. The threshold criterion was defined as obtaining  $\text{TS} < 16$  for three consecutively added new sources, denoted as  $N_{\text{TS} < 16} = 3$ . Despite iteratively adding a source at the location of the peak position in the TS map, the TS values of new sources may not decrease monotonically with iteration for several reasons. First, source positions were localized after fitting the RoI and generating the TS map. Second, some added sources were fit with a more complex spectral model than a simple PL. Finally, when creating the TS map, we fixed the source's spectral index to 2, whereas when adding the actual source to the model, we allowed its index to vary.

The specific value of  $N_{\text{TS}<16} = 3$  was chosen to avoid missing sources with  $\text{TS} \geq 25$ , the threshold commonly used for source detection in LAT data, and to optimize computation time. We tested the threshold by selecting eight representative SNRs from both complex and relatively simple regions of the sky, with both hard and soft spectral indices. We applied the above procedure to the test RoIs using a criterion of  $N_{\text{TS}<16} = 6$  and counted how many  $\text{TS} \geq 25$  sources would be excluded if a smaller  $N_{\text{TS}<16}$  criterion was used. Reducing the threshold to  $N_{\text{TS}<16} = 3$  cut only one significant source in any of the regions. Since the maximum number of sources added in any test RoI was 38, the minimum 14, and the total number of sources added across all test regions was 221, we chose to use  $N_{\text{TS}<16} = 3$  for the full sample. To allow for proper convergence of the likelihood fit, we reduced the number of free parameters prior to each new source addition. If the previously added source was between  $3^\circ$  and  $5^\circ$  of the center of the RoI, just its normalization was freed, and if greater than  $5^\circ$  all its source parameters were fixed.

To avoid having newly added sources overlap with pulsars, we deleted new sources from the RoI if they were within  $0.2^\circ$  of a  $\gamma$ -ray pulsar and refit the pulsar in the  $1 - 100$  GeV range following the 2PC conventions. 2PC modeled pulsar spectra as PL with an exponential cutoff (PLEC),

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma} \exp \left( -\frac{E}{E_c} \right)^b, \quad (5.3)$$

where  $N_0$  is the normalization factor,  $\Gamma$  is the photon spectral index,  $E_c$  the cutoff energy, and  $b$  determines to the sharpness of the cutoff. 2PC assessed the validity of fixing  $b$  to 1 in Equation 5.3 (PLEC1) by repeating the analysis using a PL model, as well as the more general exponentially cut off PL form, allowing the parameter  $b$  in Equation 5.3 to vary. For the pulsar spectra in this analysis, we compared the maximum likelihood values for spectral models with and without a cutoff and with and without the value of  $b$  being free, via  $\text{TS}_{\text{cut}} \equiv 2(\log \mathcal{L}_{\text{PLEC1}} - \log \mathcal{L}_{\text{PL}})$  and

$TS_b \equiv 2(\log \mathcal{L}_{\text{PLEC}} - \log \mathcal{L}_{\text{PLEC1}})$  to determine which to use. If  $TS_{\text{cut}} < 9$  is reported for the pulsar in 2PC then a PL model is used. If  $TS_{\text{cut}} \geq 9$ , we then check to see if the cutoff energy fit in 2PC lies within the restricted energy range of  $1 - 100$  GeV used in this work. For pulsars with cutoffs  $\geq 1$  GeV, we then use the PLEC model if  $TS_b \geq 9$ , and the PLEC model with cutoff freed otherwise. For those pulsars with cutoffs less than 1 GeV the spectral parameters are fixed to the 2PC values.

To complete the construction of our point source RoI model, we took the output of the previous steps and removed all sources with  $TS < 16$ . This final model was then used as the starting model for analyzing candidate SNR emission. We conservatively allow sources with TS down to 16 ( $\sim 4\sigma$ ) in order to account for the effects of at least the brightest sub-threshold sources on the parameter fits for the other sources in the model. Furthermore, while the SNR analysis method described in the next subsection (??) is allowed to remove sources, it cannot add them. Thus we start from a set of sources designed to allow the final model to capture all significant emission within the central region. To corroborate our method of systematically adding sources to a region, we compare our RoI source models with those found by the 2FGL approach in Appendix 5.2.

## 5.2 Comparison of Source Models with 2FGL

This SNR catalog was constructed using 3 years of P7 Source class data in the energy range  $1 - 100$  GeV, whereas 2FGL used 2 years of data over the larger energy range  $0.1 - 100$  GeV. The differences in observing time and energy range resulted in residual, unmodeled emission in some RoIs as well as changes to some 2FGL sources' spectral model, position localization, and detection significance. Here we compare the input source models constructed for this catalog, described in Section 5.1, with

2FGL to better understand the method’s ability to describe the regions studied. Since we rederive the input source model only within a  $3^\circ$  radius of the center of each RoI, we consider sources only inside that radius.

Given the data set differences, in each RoI we expect similar but not identical numbers of sources relative to those in 2FGL. Figures 5.1 and 5.2 show the numbers of significant ( $TS \geq 25$ ) 2FGL sources and derived input model sources (excluding 2FGL identified AGN and pulsars kept in the input model) in individual RoIs as 2D histograms. In Figure 5.1, the number of sources in the derived input model is typically greater than the number of 2FGL sources that are significant at  $1 - 100$  GeV. 73 of the 279 RoIs studied contain at least one of the the 12 extended 2FGL sources. Since 2FGL extended sources were removed from the inner  $3^\circ$  of each RoI, and this region was repopulated with point sources, we can detect multiple point sources inside the extent of any removed extended 2FGL sources. This decomposition of extended sources, combined with the longer data set and different energy range compared to 2FGL, contribute to the high ratio of input model to 2FGL sources in some RoI, which demonstrates the need to rederive the source model.

To more accurately represent the 2FGL sources being reproduced in the central  $3^\circ$ , in Figure 5.2 we limited the input model sources to those within  $0.2^\circ$  (approximately the width of the core of the 10 GeV PSF) of a 2FGL source, effectively excluding input sources that are not co-spatial with a 2FGL source. Here we see that the majority of 2FGL sources have counterparts in the rederived set. As a region’s complexity increases, seen as an increase in numbers of 2FGL sources, up to about half of the 2FGL sources may not have counterparts within  $0.2^\circ$ . Given that in these same regions we have more new sources than 2FGL sources, as seen in Figure 5.1, we find as expected that the longer data set with improved statistics at higher energies, where the angular resolution of the LAT is the best, allows us to

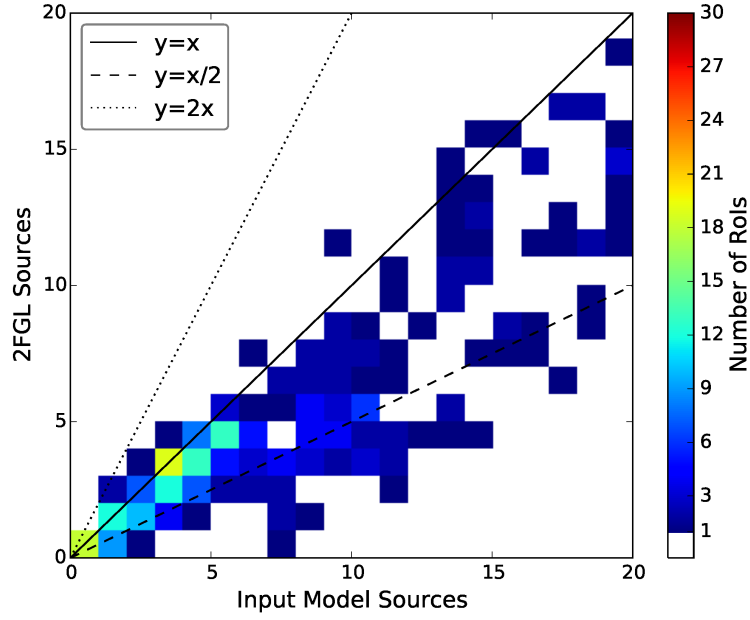


Figure 5.1: Comparison of the number of 2FGL sources with  $TS_{1-100\text{ GeV}} \geq 25$  (excluding AGN and pulsars) with the number of newly added input model sources in the present analysis, for sources within  $3^\circ$  of the center of each RoI. The color scale shows the number of RoIs with a particular combination of numbers of 2FGL sources and new sources. White corresponds to no RoI with that combination of source counts.

add new sources to account for newly significant excesses in these complex regions. Additionally, sources with low TS in 2FGL are particularly susceptible to having a newly added source which may start at a similar position but then localize further than  $0.2^\circ$  from the 2FGL source.

Thus, we find that the method developed and used here produces a model which reproduces the 2FGL sources as expected, including differences that trend as anticipated given the longer data set and modified energy range, yielding better spatial resolution. The new method thus provides reasonable representations of the regions being modeled as input for the final analysis.



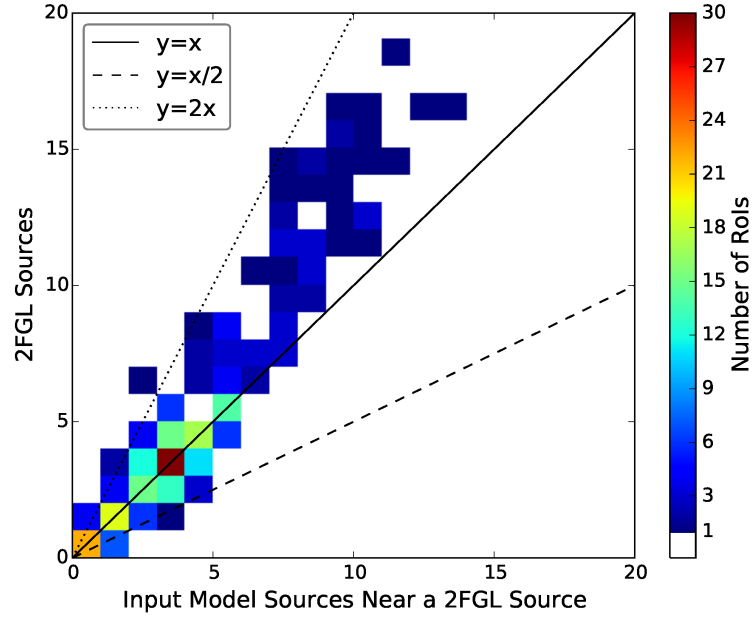


Figure 5.2: Same as Figure 5.1, including only input model sources lying within  $0.2^\circ$  of a 2FGL source.

### 5.3 Summary

In this chapter, we have presented results from the publication of the SNRcat. Application of addSrcs adding point sources to characterize emission in anregion of interest (RoI). Give more details on validation and testing than was given in the paper, as well as details on the code. Work on fitting single extended source, present some work on detected SNRs and population properties, implications for total power in cosmic rays (don't focus on this because it wasn't where I contribute the most). Mock catalog contributions. Testing with extended sources or don't mention too much because we decide not to apply it here?

# Chapter 6

## Extended Source Detection above 50 GeV: The 2FHL Catalog

Application of addSrcs searching for extended (and really point too) sources in the sky. 2FHL results on all Galactic sources. Index histograms for entire Second Catalog of Hard Fermi-LAT Sources (2FHL) population showing harder index for Galactic sources.

We don't just detect extended though! The pipeline was built to try extended and if that's not likely, revert to point source. Simple check with Alberto's pipeline to show we didn't detect any glaring discrepancies. Quick check of Alberto's results for clusters of point source at  $|b| < 10^\circ$ .

How much of the 2FHL paper can I put in as is, how much can I take with modifications?

Below is if I just took the sections describing extend sources.

## 6.1 Extended Sources Previously Detected by the LAT

We explicitly modeled sources as spatially extended when a previous, dedicated, analysis found the source to be resolved by the LAT. The 25 extended sources reported in 3FGL were included in our model using the spatial templates derived in the individual source studies (see references in Acero et al. 2015). Refitting the positions and extensions of the 3FGL extended sources in this energy range is beyond the scope of this work.

Of the 25 3FGL extended sources, 19 are significantly detected here above the detection threshold ( $TS \geq 25$ ). Only 6 sources are not detected and, since all have  $TS < 10$ , are removed from the sky model (see §6.3 for details).

One extended LAT source has had a dedicated analysis published since the release of the 3FGL catalog. Abramowski et al. (2015a) reported joint H.E.S.S. and LAT observations of the very high energy (VHE) source HESS J1834-087. This source is coincident with supernova remnant (SNR) W41 and was detected as spatially extended in a wide energy range spanning 1.8 GeV to 30 TeV. In this paper, we employ the spatial model for the GeV emission determined in Abramowski et al. (2015a), leading to a significant detection of this source.

## 6.2 Newly Detected Extended Sources

In addition to modeling the extended sources mentioned in §6.1, we performed a blind search of the Galactic plane ( $|b| < 10^\circ$ ) to identify potential extended sources not included in previously published works. Our analysis pipeline is similar to that used in Hewitt et al. (2013), with some modifications tailored to searching for

multiple extended sources in an ROI. The pipeline employs the `pointlike` binned maximum likelihood package (Kerr 2010), in particular utilizing the extended source fitting tools validated by Lande et al. (2012) to simultaneously fit the position, extension, and spectra of sources in our ROI.

We created 72 ROIs of radius  $10^\circ$ , centered on  $b = 0^\circ$  with neighboring ROIs overlapping and separated by  $5^\circ$  in Galactic longitude. Our initial model of the  $\gamma$ -ray emission in each ROI consisted solely of the Galactic diffuse (allowing just the normalization to be fit) and isotropic emission models (fixing the normalization), with no other sources in the ROI. Emission in the ROIs was further characterized by adding sources and fitting their spectral parameters (normalization and spectral index) in a  $14^\circ \times 14^\circ$  region.

A TS map, that included all significant sources found previously, made up of  $0.1^\circ \times 0.1^\circ$  bins across the ROI, was created at each iteration and a small radius ( $0.1^\circ$ ) uniform disk, with a power-law spectrum was placed at the position of the peak TS pixel. The spectra of any newly added sources, as well as the position, extension, and spectral parameters of the disk were then fit. If  $\text{TS}_{\text{ext}} \geq 16$ , where  $\text{TS}_{\text{ext}} = 2 \log(\mathcal{L}_{\text{ext}}/\mathcal{L}_{\text{ps}})$  (i.e. twice the logarithm likelihood ratio of an extended to a point source, Lande et al. 2012), then the disk was kept in the model. For  $\text{TS}_{\text{ext}} < 16$ , the extended source was replaced by a point source with a power-law spectral model. For the point-source replacement case, spectral parameters of sources in the ROI were fit and the position of the new point source was optimized. Finally, the spatial parameters of any previously added extended sources were refit iteratively before creating a new TS map and repeating the process. We stopped adding sources when the peak TS was less than 16 for two successive sources.

To assess the impact of fitting extended sources when starting with an ROI devoid of sources, a crosscheck analysis (also using `pointlike`) was performed across

the Galactic plane. We included 3FGL point and extended sources, the Galactic diffuse and isotropic emission, and pulsars from the second *Fermi*-LAT pulsar catalog (Abdo et al. 2013) (as well as from 3FGL) in the preliminary source model for each region. Sources were iteratively added to account for residual emission and both these residual sources and 3FGL sources were tested for extension. Remarkably, this alternative analysis converges (i.e. spectral and spatial parameters for the detected extended sources are compatible in both analyses) to the initially source-devoid analysis for nearly all detected extended sources.

Extended sources detected in the analysis described in this section for which the position and extension were compatible with those found by the crosscheck were included in the ROI model at step 1 of the full ML analysis detailed in §???. Seed point sources interior to the extended sources were removed prior to the ML fit. To address the ambiguity between detecting a source as spatially extended as opposed to a combination of point sources, we utilized the algorithm detailed in Lande et al. (2012) to simultaneously fit the spectra and positions of two nearby point sources. We only consider a source to be extended if  $TS_{\text{ext}} > TS_{2\text{pts}}$  (improvement when adding a second point source). Our blind search of the Galactic plane allowed us to find 5 sources not previously detected as extended by *Fermi*-LAT. Further details on these sources are presented in § 6.3.

## 6.3 Extended Source Results

In total, 31 sources are modeled as spatially extended and input into the ML analysis: 25 listed in 3FGL, 5 sources detected in the `pointlike` analysis (described in § 6.1) that were not detected as extended at the time of 3FGL, and one, SNR W41, reported recently by both the H.E.S.S. and LAT teams (Abramowski et al. 2015a).

Names and properties of the extended sources are provided in Tables 6.1 and 7.2. Six extended sources, detected in 3FGL, were not detected in 2FHL: the SMC, S 147 (the point source 2FHL J0534.1+2753 was detected inside it), the lobes of Centaurus A (although we detect its core as a point source, 2FHL J1325.6–4301), W 44, HB 21 and the Cygnus Loop.

We detect a weak source, 2FHL J1714.1–4012 ( $TS = 27$ ), just outside the southwestern edge of the 3FGL spatial template used to model the emission from SNR RX J1713.7–3946 (2FHL J1713.5–3945e). 2FHL J1714.1–4012 has a hard spectral index  $\Gamma = 1.63 \pm 0.38$ , that is within errors of the spectral index derived for the SNR,  $\Gamma = 2.03 \pm 0.20$ . It is unclear whether 2FHL J1714.1–4012 is a distinct source separated from the SNR, or the result of un-modeled residual emission due to an imperfection in the spatial template adopted for the extended source.

2FHL J1836.5–0655e is associated with the PWN HESS J1837–069. The 3FGL catalog contains several point sources in the vicinity of the PWN. We detect three sources in the vicinity, 2FHL J1834.5–0701, 2FHL J1837.4–0717 and 2FHL J1839.5–0705, the first two of which are coincident with 3FGL sources (3FGL J1834.6–0659, 3FGL J1837.6–0717 respectively). The power-law spectral indices of the three 2FHL point sources and 2FHL J1836.5–0655e are all consistent with each other. The concentration of sources around HESS J1837–069 combined with the spectral compatibility of the sources is suggestive of a common origin to the  $\gamma$ -ray emission in this region. However, the surrounding  $\gamma$  rays could arise from other sources in the region (Gotthelf & Halpern 2008); further analysis is necessary to determine the nature of the sources in this region.

A brief description of the five new 2FHL extended sources is given below with residual TS maps for the region surrounding each source shown in Figure 6.1. Detailed analyses of these new extended sources will be reported in separate papers.

**2FHL J1443.2–6221e** overlaps with the young, radio-detected SNR RCW 86 (G315.42.3). RCW 86 is a 42' diameter SNR that lies at a distance of 2.3-2.8 kpc and is likely associated with the first recorded supernova, SN 185 AD (Rosado et al. 1996; Sollerman et al. 2003). With more than 40 months of data and using the **P7SOURCE** dataset, the LAT did not significantly detect the SNR, but upper limits on detection at GeV energies combined with detection of significant extension in the TeV (Aharonian et al. 2009) were sufficient to strongly favor a leptonic origin for the emission (Lemoine-Goumard et al. 2012).

An updated LAT analysis of RCW 86 using 76 months of data, as well as the Pass 8 event-level analysis, resulted in detection of the SNR by the LAT as well as significant extension measurement (Hewitt & Fermi-LAT Collaboration 2015). In this paper, we report the results derived for **2FHL J1443.2–6221e** from the **pointlike** analysis described in § 6.1.

**2FHL J1419.2–6048e** is a newly detected extended sources with size  $\sigma_{\text{disk}} = 0.36^\circ \pm 0.03^\circ$ , that overlaps two nearby PWN/PSR complexes in the Kookaburra region. In the southwest of Kookaburra, HESS J1418–609 (Aharonian et al. 2006) is coincident with both the extended non-thermal X-ray “Rabbit” PWN (G313.3+0.1, Roberts et al. 1999), and the  $\gamma$ -ray detected pulsar PSR J1418–6058 (Abdo et al. 2009). The northeast region, called “K3”, contains HESS J1420–607, coincident with PWN G313.5+0.3 and PSR J1420–6048. Acero et al. (2013) detected, with *Fermi*-LAT, emission from both HESS J1418–609 (with a soft spectral index, pulsar-like spectrum) and HESS J1420–607 (with a hard power-law index) above 10 GeV, but only HESS J1420–607 was significantly detected above 30 GeV. Neither showed significant extension. Our result for the fitted power-law spectral index of **2FHL J1419.2–6048e** is in agreement with the previous GeV and TeV results, yet our measured radius is considerably larger than the TeV extension. To compare the ex-

tensions of the uniform disk model used for 2FHL J1419.2–6048e in this paper to the Gaussian model of Aharonian et al. (2006), we defined the radius which contains 68% of the source’s intensity as  $r_{68}$ , with  $r_{68,\text{Gaussian}} = 1.51\sigma$ , and  $r_{68,\text{disk}} = 0.82\sigma$  (Lande et al. 2012). We find that  $r_{68} \simeq 0.30^\circ$  for 2FHL J1419.2–6048e, and  $r_{68} \simeq 0.09^\circ$  for HESS J1420–607.

**2FHL J1355.2–6430e**, coincident with the VHE source HESS J1356–645, is detected as extended ( $\sigma_{\text{disk}} = 0.57^\circ \pm 0.02^\circ$ ) for the first time by the LAT in this work. The source HESS J1356–645 (Abramowski et al. 2011) is associated with the pulsar PSR J1357–6429, which was determined to be powering a surrounding extended radio and X-ray PWN (Lemoine-Goumard et al. 2011). Acero et al. (2013) detected faint emission from the nebula, and derived a 99% c.l. Bayesian upper limit on extension ( $\sigma_{\text{Gauss}} < 0.39^\circ$ ) in the absence of significant extension. The fitted spectral index for 2FHL J1355.2–6430e is compatible with the GeV and TeV results (Abramowski et al. 2011; Acero et al. 2013), however, the fitted disk extension is larger than that of the TeV detection, with  $r_{68} \simeq 0.47^\circ$  for 2FHL J1355.2–6430e and  $r_{68} \simeq 0.30^\circ$  for HESS J1356–645.

**2FHL J1112.4–6059e** is an extended source ( $\sigma_{\text{disk}} = 0.53^\circ \pm 0.03^\circ$ ) newly detected by the LAT that encircles two 3FGL sources, 3FGL J1111.9–6058 and 3FGL J1111.9–6038, and has another, 3FGL J1112.0–6135, just outside its boundary (Acero et al. 2015). The extended source also partially overlaps the massive star forming region NGC 3603.

Finally, **2FHL J0431.2+5553e** is a large extended source ( $\sigma_{\text{disk}} = 1.27^\circ \pm 0.04^\circ$ ), with a hard spectrum, that has not been previously detected at  $\gamma$ -ray energies. It overlaps the recently discovered radio SNR G150.3+4.5 (Gao & Han 2014). G150.3+4.5 is a  $2.5^\circ \times 3^\circ$  (Galactic coordinates) elliptical shell type SNR that has a steep radio synchrotron spectrum ( $\alpha = -0.6$ ), indicative of radio SNRs.



Table 6.1. 2FHL extended sources previously detected by the *Fermi*-LAT

2FHL Name	$l$ [deg]	$b$ [deg]	TS	Association	Class	Spatial model	Extension [deg]
J0526.6–6825e	278.843	-32.850	49.80	LMC	gal	2D Gaussian	1.87
J0617.2+2234e	189.048	3.033	398.64	IC 443	snr	2D Gaussian	0.27
J0822.6–4250e	260.317	-3.277	63.87	Puppis A	snr	Disk	0.37
J0833.1–4511e	263.333	-3.104	49.70	Vela X	pwn	Disk	0.91
J0852.8–4631e	266.491	-1.233	437.21	Vela Jr	snr	Disk	1.12
J1303.4–6312e	304.235	-0.358	56.06	HESS J1303–631	pwn	2D Gaussian	0.24
J1514.0–5915e	320.269	-1.276	165.51	MSH 15–52	pwn	Disk	0.25
J1615.3–5146e	331.659	-0.659	128.15	HESS J1614–518	spp	Disk	0.42
J1616.2–5054e	332.365	-0.131	87.18	HESS J1616–508	pwn	Disk	0.32
J1633.5–4746e	336.517	0.121	114.17	HESS J1632–478	pwn	Disk	0.35
J1713.5–3945e	347.336	-0.473	60.98	RX J1713.7–3946	snr	Map	0.56
J1801.3–2326e	6.527	-0.251	50.20	W 28	snr	Disk	0.39
J1805.6–2136e	8.606	-0.211	160.43	W 30	snr	Disk	0.37
J1824.5–1350e	17.569	-0.452	266.09	HESS J1825–137	pwn	2D Gaussian	0.75
J1834.9–0848e	23.216	-0.373	67.30	W 41	spp	2D Gaussian	0.23
J1836.5–0655e	25.081	0.136	62.72	HESS J1837–069	pwn	Disk	0.33
J1840.9–0532e	26.796	-0.198	163.15	HESS J1841–055	pwn	Elliptical 2D Gaussian	0.62, 0.38, 39
J1923.2+1408e	49.112	-0.466	44.60	W 51C	snr	Elliptical Disk	0.38, 0.26, 90
J2021.0+4031e	78.241	2.197	115.97	Gamma Cygni	snr	Disk	0.63
J2028.6+4110e	79.601	1.396	28.09	Cygnus Cocoon	sfr	2D Gaussian	3.0

Note. — List of the 20 extended sources in the 2FHL that were previously detected as extended by the *Fermi*-LAT. All these sources are in 3FGL except W41, which is studied by Abramowski et al. (2015b). The Galactic coordinates  $l$  and  $b$  are given in degrees. The extension of the disk templates is given by the radius, the extension of the 2D Gaussian templates is given by the  $1\sigma$  radius, and the elliptical templates are given by the semi-major axis, semi-minor axis, and position angle (East of North).

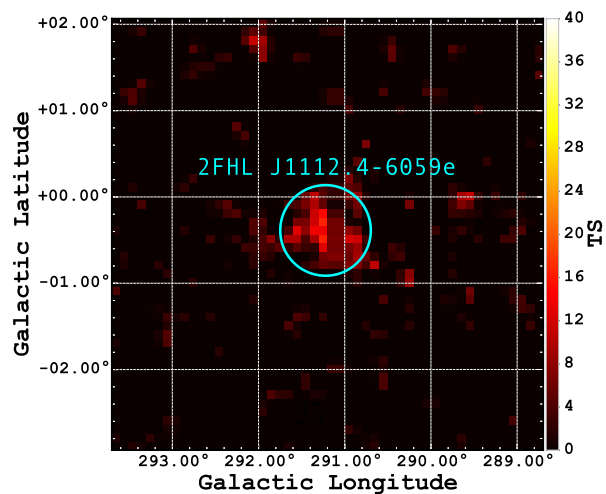
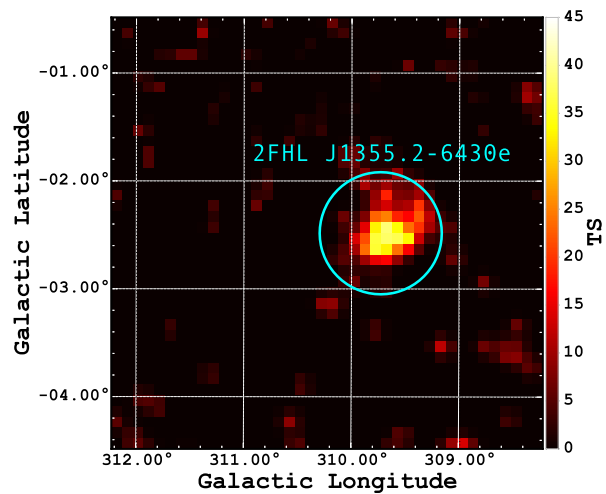
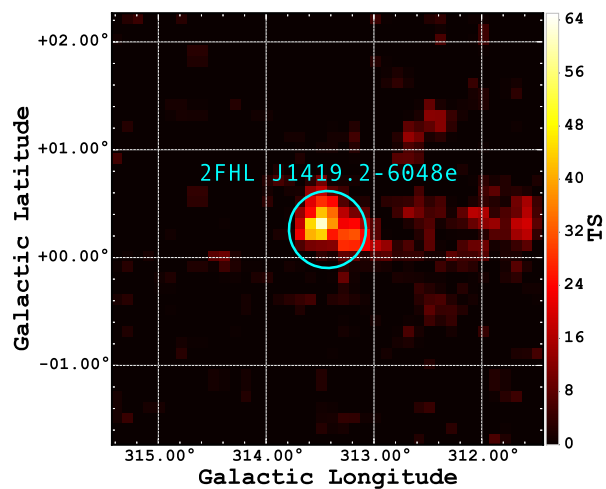
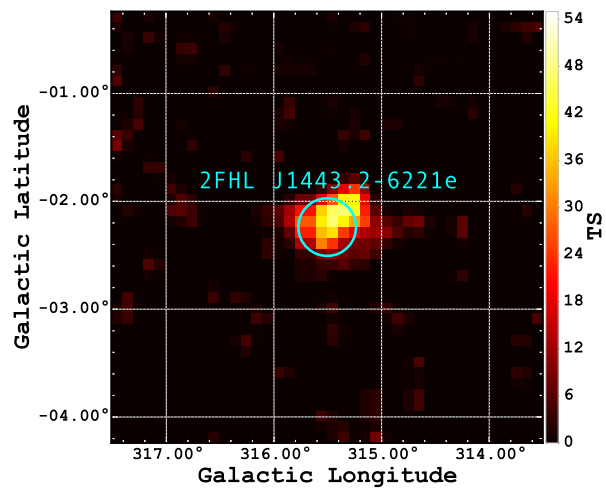
## 6.4 Summary

In this chapter, we have presented the publication on 2FHL, focusing primarily on the Galactic results of the publication and in particular detected extended sources. Extension of addSrcs to search for spatially extended sources, applied to 8 years [JAM: check] of LAT data above 50 GeV. Detected x extended. y were known 3FGL, z were new;y detected as extended at GeV energies, SNR G150.3+4.5 was brand new. Galactic seem to have harder indices than extra gal, suggests which unid'd in the plane are gal vs. egal. All extended harder than diffuse. Hints of different morphology between 2FHL and 2FGL, didn't study here, but this is one of the motivations for > 10 GeVstudy.

Table 6.2. New 2FHL extended sources

2FHL Name	$l$ [deg]	$b$ [deg]	TS	$TS_{ext}$	$TS_{2pts}$	$F_{50}$	$\Delta F_{50}$	$\Gamma$	$\Delta\Gamma$	Association	Class	Radius [deg]
J0431.2+5553e	150.384	5.216	87.9	83.4	26.2	11.70	2.11	1.66	0.20	G 150.3+4.5	snr	1.27
J1112.4−6059e	291.222	-0.388	80.9	68.3	22.5	12.80	2.36	2.15	0.28	PSR J1112−6103	pwn	0.53
J1355.2−6430e	309.730	-2.484	82.3	31.8	12.9	9.59	1.95	1.56	0.22	PSR J1357−6429	pwn	0.57
J1419.2−6048e	313.432	0.260	109.3	49.1	15.6	17.60	2.80	1.87	0.19	PSR J1420−6048	pwn	0.36
J1443.2−6221e	315.505	-2.239	75.6	29.9	19.2	7.23	1.70	2.07	0.30	SNR G315.4−2.3	snr	0.27

Note. — List of the 5 new extended sources in the 2FHL. All these sources are characterized by an uniform disk template whose radius is given in the last column.



# Chapter 7

## SNR G150.3+4.5

Dedicated analysis of one interesting 2FHL result. First blindly detected extended  $\gamma$ -ray source. Large size + HI suggest it's near, hard spectrum looks like pwn, but size matches with radio SNR.

Take this all straight from the paper I write.

### 7.1 Summary

[JAM: most of this should be the conclusions from the G150 paper] In this chapter, we have presented the publication on the dedicated analysis of the extended  $\gamma$ -ray emission detected in the direction of SNR G150.3+4.5. SNR G150.3+4.5 was first detected in radio by Gao & Han (2014), and subsequently detected in  $\gamma$ -rays in 2FHL above 50 GeV. We discussed our LAT morphological analysis at energies  $E \geq x$  GeV and spectral analysis down to  $E \geq 750$  MeV, demonstrating a change in extension and centroid position compared to the 2FHL result. Discuss potential source origin scenarios. Is it SNR or PWN? Is 2FHL source same as  $> \text{few GeV}$ ?

[JAM: for diss, not paper]. The way this figures into the whole is that this is a follow up analysis of one of the most interesting sources detected with addSrcs, and,

(hopefully!), we're able to say something about the source and nature of the  $\gamma$ -ray emission, relation to SNR and 2FHL source1

## 7.2 Introduction

Supernova remnants have long been thought to be the primary accelerators of cosmic rays up to the knee of the cosmic ray energy spectrum.

what to say about radio SNRs? Connect CRs to nonthermal emission and the LAT and Something about SNRs, cosmic ray accelerators, radio detections, connection between radio-LAT observations, G150 detection, 2FHL blind detection and SNRs at TeV (all young?), this paper extends the energy down to

Focus more on the hadronic vs leptonic since that's what's interesting? We describe the LAT and analysis results in §7.3, detail multiwavelength observations in §7.4, and discuss various emission origin scenarios in §7.5.

## 7.3 *Fermi* LAT Observations and Analysis

### 7.3.1 Data Set and Reduction

*Fermi* LAT is a pair conversion telescope sensitive to high energy  $\gamma$ -rays from 20 MeV to greater than 1 TeV (Ackermann et al. 2016), operating primarily in a sky-survey mode which views the entire sky every 3 hours. The LAT has wide field of view ( $\sim 2.4$  sr), a large effective area of  $\sim 8200$  cm<sup>2</sup> above 1 GeV for on axis events and a 68% containment radius angular resolution of  $\sim 0.8^\circ$  at 1 GeV. For further details on the instrument and its performance see Atwood et al. (2009) and Ackermann et al. (2012).

In this analysis, we analyzed 7 years of Pass 8 data, from August 2nd 2008 to

August 2nd 2015. The Pass 8 event reconstruction provides a significantly improved angular resolution [JAM: this is sadly unimportant unless I'm at higher energy or using the PSF types. The P8 total PSF at 1 GeV is about the same as for P7REP. It's the acceptance/effective area that are considerably better at this energy], acceptance, and background event rejection (Atwood et al. 2013a,b), all of which lead to an increase in the effective energy range and sensitivity of the LAT. Source class events were analyzed within a  $14^\circ \times 14^\circ$  region centered on SNR SNR G150.3+4.5 using the P8R2\_SOURCE\_V6 instrument response functions, with a pixel size of  $0.1^\circ$ . To reduce contamination from earth limb  $\gamma$ -rays, only events with zenith angle less than  $100^\circ$  were included.

For spectral and spatial analysis we utilized both the standard *Fermi*Science Tools (version 10-01-01)<sup>1</sup>, and the binned maximum likelihood package *pointlike* (Kerr 2010). *pointlike* provides methods for simultaneously fitting the spectrum, position, and spatial extension of a source, and was extensively validated in Lande et al. (2012). Both packages fit a source model, the Galactic diffuse emission, and an isotropic component (which accounts for the background of misclassified charged particles and the extragalactic diffuse  $\gamma$ -ray background)<sup>2</sup> to the observations. In this analysis, we used the standard Galactic diffuse ring-hybrid model scaled for Pass 8 analysis, *gll\_iem\_v06.fits* (modulated by a power law function with free index and normalization), and for the isotropic emission, we used *iso\_P8R2\_SOURCE\_V6\_v06.txt*, extrapolated to 2 TeV as in Ackermann et al. (2016).

In our source model for the region, we included sources from the third *Fermi* LATcatalog (Acero et al. 2015, 3FGL) within  $15^\circ$  of the center of our region of interest (RoI). We replaced the position and spectrum of any 3FGL pulsars in the

---

<sup>1</sup><http://fermi.gsfc.nasa.gov/ssc/>

<sup>2</sup><http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

region with their corresponding counterpart from the LAT 2nd pulsar catalog (Abdo et al. 2013). Residual emission unaccounted for by 3FGL sources is present in the RoI due to the increased time range and different energy selection with respect to that in 3FGL. We added to the RoI several point sources to account for this unmodeled emission and minimize the global residuals. [JAM: do I need to say more about these sources? should I mention adding them automatically and iteratively based on TS maps and reference SNRcat/2FHL? How close is the closest source? Mention this and use as an argument for not saying much more about them]. The normalization and spectral index of sources within  $5^\circ$  of the center of the RoI were free to vary, whereas all other source parameters were fixed. A preliminary maximum likelihood fit of the RoI was performed, and sources with a test statistic (TS)  $< 9$  (TS is defined as,  $TS = 2 \text{Log}(\mathcal{L}_1/\mathcal{L}_0)$  where  $\mathcal{L}_1$  is the likelihood of source plus background and  $\mathcal{L}_0$  that of just the background) were removed from the model.

### 7.3.2 Morphological Analysis

Studying the spatial extension of sources with the LAT is non-trivial due to the energy-dependent point spread function (PSF) and strong diffuse emission present in the Galactic plane. Soft spectrum point sources and uncertainties in the diffuse model can be a source of systematic error when not accurately modeling extended emission as such, particularly at low energies where the PSF is broad. To strike a balance between the best angular resolution and minimal source and diffuse contamination, we restrict our morphological analysis to energies between 1 GeV and 1 TeV. We divide this energy range into 12 [JAM: 4bpd] logarithmically spaced bins for both `pointlike` and `gtlike` binned likelihood analyses.

Three unidentified 3FGL sources are located within the extent of SNR G150.3+4.5. 3FGL J0425.8+ 5600, located approximately  $0.6^\circ$  from the center of the SNR,

is the closest of the three sources and is described with a power law spectrum of index  $\Gamma = 2.35 \pm 0.17$  in the 3FGL catalog. The closest radio source to 3FGL J0425.8+5600 is NVSS J042719+560823, at 0.25 away (Ref?). 3FGL J0423.5+5442, exhibits a power law spectral index,  $\Gamma = 2.63 \pm 0.15$ , with no clear multiwavelength source association. Finally, 3FGL J0426.7+5437 has a pulsar-like spectrum, yet in a timing survey performed with the 100-m Effelsberg radio telescope, Barr et al. (2013) were unable to detect pulsations from the source down to a limiting flux density of  $\sim 0.1$  mJy. The source is located about  $0.8^\circ$  from the center of the SNR. We discuss this source and potential association with SNR G150.3+4.5 further in §7.5.2).

In our analysis, we removed 3FGL J0425.8+5600 and 3FGL J0423.5+544 from the RoI, but kept 3FGL J0426.7+5437 in the model since preliminary analyses showed clear positive residual emission at the position of the source if it was removed from the RoI. Figure 7.1 shows a residual TS map for the region around SNR G150.3+4.5. This point source detection-significance map was created by placing a point source modeled with a power law of photon index,  $\Gamma = 2$  at each pixel and gives the significance of detecting a point source at each location above the background.

We modeled the excess emission in the direction of SNR G150.3+4.5 with a uniform intensity, radially-symmetric disk, simultaneously fitting the spatial and spectral components of the model via `pointlike`. The extension of the disk was initialized with a seed radius of  $\sigma = 0.1^\circ$  and position centered on the radio position of SNR G150.3+4.5. We define the significance of extension as in Lande et al. (2012);  $\text{TS}_{\text{ext}} = 2 \log(\mathcal{L}_{\text{ext}}/\mathcal{L}_{\text{ps}})$ , with  $\mathcal{L}_{\text{ext}}$  being the likelihood of the model with the extended source and  $\mathcal{L}_{\text{ps}}$  that with of a point source located at the peak of emission interior to the extended source. For the disk model,  $\text{TS}_{\text{ext}} = 298$ , with a best fit



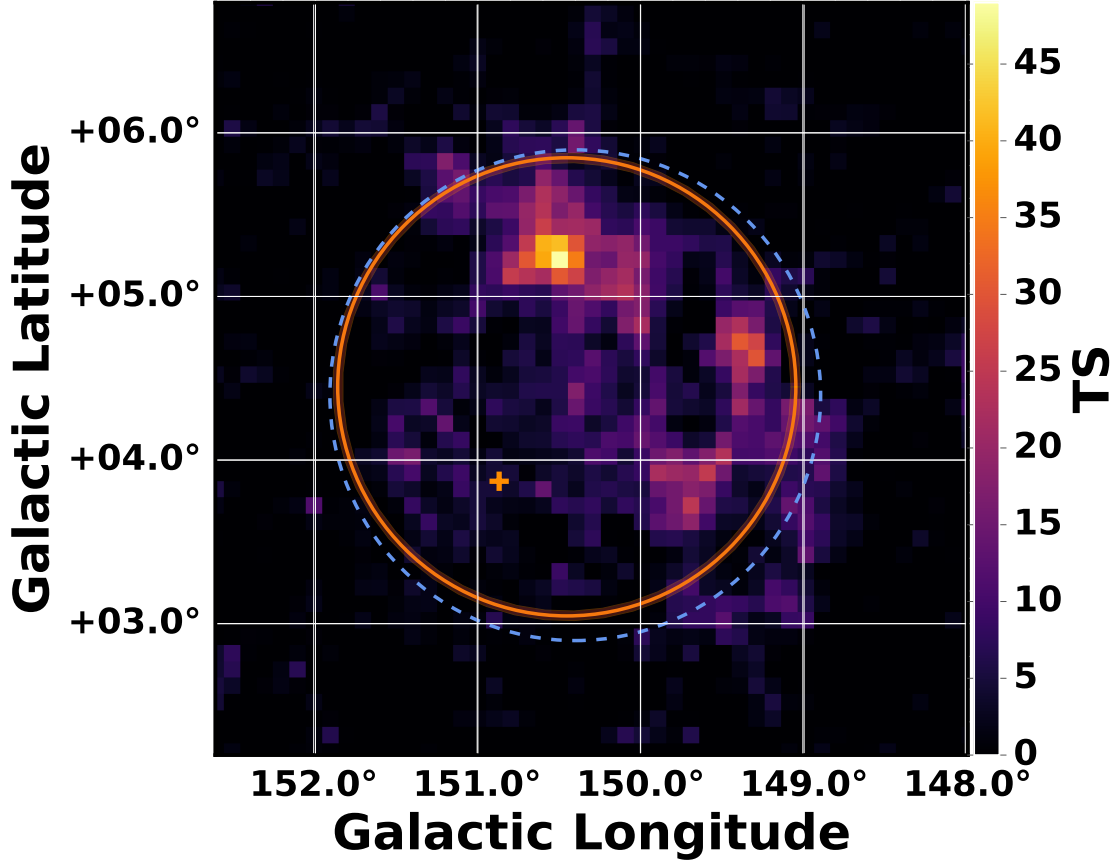


Figure 7.1: Background subtracted residual TS map above 1 GeV with  $0.1^\circ \times 0.1^\circ$  pixels for fixed index  $\Gamma = 2$ , centered on SNR SNR G150.3+4.5. The orange circle and translucent shading show the fit disk radius and  $1\sigma$  errors, respectively, for the extended source, the orange cross shows the position of 3FGL J0426.7+5437 (included in the background model), and blue dashed circle is the extent of the radio SNR.

radius,  $\sigma = 1.40^\circ \pm 0.03^\circ$  [JAM: I should just put this all in a table and reference it], which is in excellent agreement with the radio size of the SNR determined in Gao & Han (2014). We tried adding back in to our model the two removed 3FGL sources but both were insignificant when fit on top of the best fit disk. Figure 7.2 is a Residual TS map of the same region as Figure 7.1, but with the disk source included in the background showing that the disk can account well for the emission in the region.

The morphology of the radio emission is suggestive of an elliptical or ring mor-

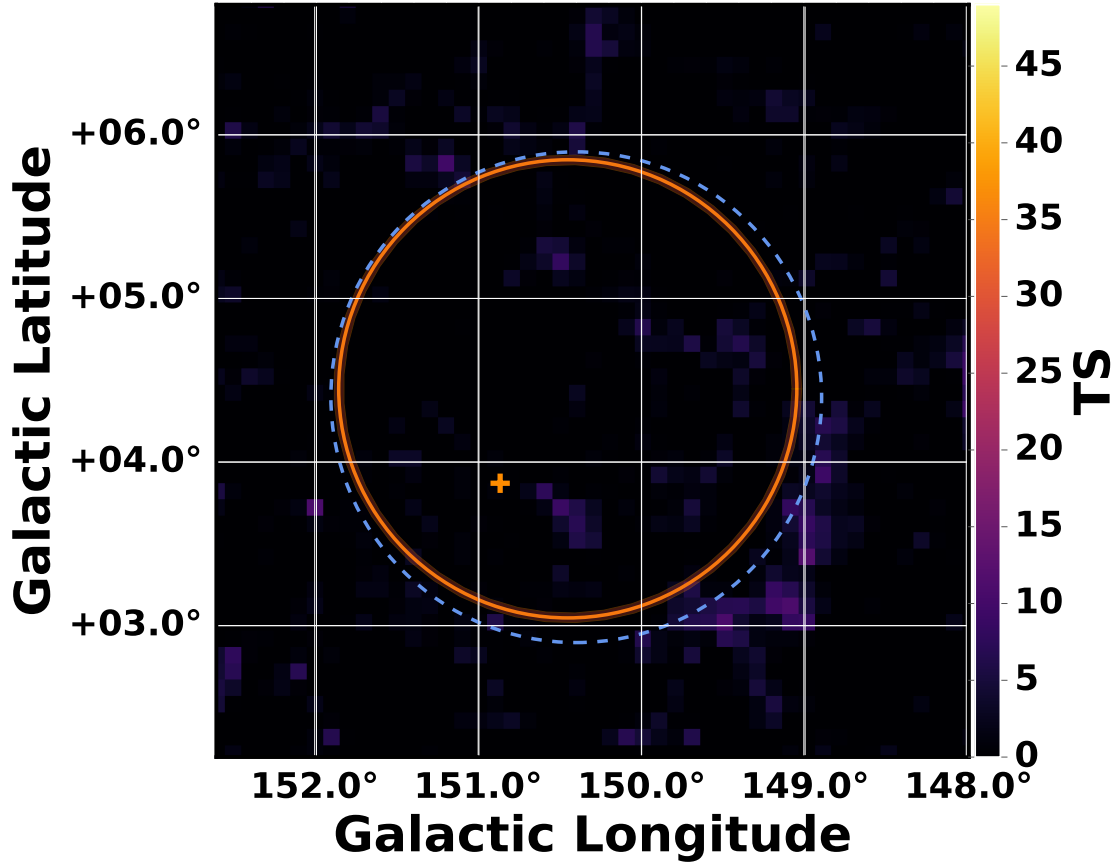


Figure 7.2: Same as Figure 7.1 but with disk in the background model [JAM: should this be a residual counts map instead?]

phology, so an elliptical disk and ring spatial model were tested as well. For the ring model, the fit reduced to a disk with parameters matching those stated above. Using the elliptical model showed a weak improvement over the radially symmetric model at the  $2.6\sigma$  level ( $\Delta\text{TS} = 9$  with two additional degrees of freedom), which we did not consider significant enough to say the GeV emission had an elliptical morphology (see Table ??). For the remainder of this study, we only considered the disk spatial model.[JAM: put Edisk in table too and reference i.] [JAM: I should double check this for 1GeV- 1TeV. I was done for 1-562 GeV, wait till addSrcs is done]

Other things we tried

Table 7.2. New 2FHL extended sources

Spatial Model <sup>a</sup>	TS	TS <sub>ext</sub>	$\sigma$ °	Association	Class	Spatial model	Extension [deg]
J0526.6–6825e	278.843	-32.850	49.80	LMC	gal	2D Gaussian	1.87
J0617.2+2234e	189.048	3.033	398.64	IC 443	snr	2D Gaussian	0.27
J0822.6–4250e	260.317	-3.277	63.87	Puppis A	snr	...	0.37

Note. — This is mostly from 2FHL, just playing with the table. Don't need a table for just disk hypothesis, but maybe to have disk 3 point sources comparison. I tried adding more sources on top of the 3FGL sources and there's no significant residual. where to say something about testing searching for point sources overlapping the extended source and trying to fit an extended source on top as well? in this table give the disk model with best spectral spatial params, TS, TSext dof, LL, then the model with just the 3 3FGL sources (no disk) spectrum of each, TS, dof + LL( didn't relocalize the se sources), separate spatial spectral tables?

<sup>a</sup>comments and notes?

fitting an extended source (starting with the 2FHL result) on top of the one currently there. Insignif. idk what to say about 2FHL yet.

another starting at the position of G149. Insignif

Say something about why we don't just go with the 3 3FGL sources. In the table I shouldn't just compare the 3 to the disk though because I also keep J0426 in the model. So the base comparison is really 2 sources vs the disk. Maybe it's enough to just say of course we keep the disk, we find one at GeV that matches really well with the radio. What did Josh's paper say about how modelling the spectrum of an intrinsically extended source as point sources skews the PS spectrum to softer energies?

He said, "Specifically, modeling a spatially extended source as point-like will systematically soften measured spectra", but idk if I get why. We see it with the 2 3FGL sources being softer than what the disk winds up being

Another thing to point out is how modeling as point vs extended, if it's really extended can affect the fit of other point sources nearby, like J0426, so I should show the spectrum of this source too? I fit both the norm and index of the source.

### 7.3.3 Spectral Analysis

After determining the best fit morphology with `pointlike` for the GeV emission coincident with SNR SNR G150.3+4.5, we used those results as a starting point for our `gtlike` maximum likelihood fit of the region to estimate the best spectral parameters for our model. The LAT data is well described by a power law across the entire energy range with a photon index,  $\Gamma = 1.80 \pm 0.04$ , and energy flux above 1 GeV of  $(7.17 \pm 0.73 \times 10^{-11}) \text{ erg cm}^{-2} \text{ s}^{-1}$  and  $\text{TS} = 373$  [JAM: these are the point-like results, change them when I get the gtlike res]. We tested the  $\gamma$ -ray spectrum of the extended disk for spectral curvature using a log-normal model (Log Parabola), and find no significant deviation from a power law ( $\Delta\text{TS} \sim 1$ ).

Still to do

`gtlike`

Systematics. Bracketing IRFs, alt iem, try varying the extension? still need to be done. Should probably just move this into the spectral section

## 7.4 Multiwavelength Observations and Analysis

### 7.4.1 HI

### 7.4.2 CO?

Do the CO maps add anything?

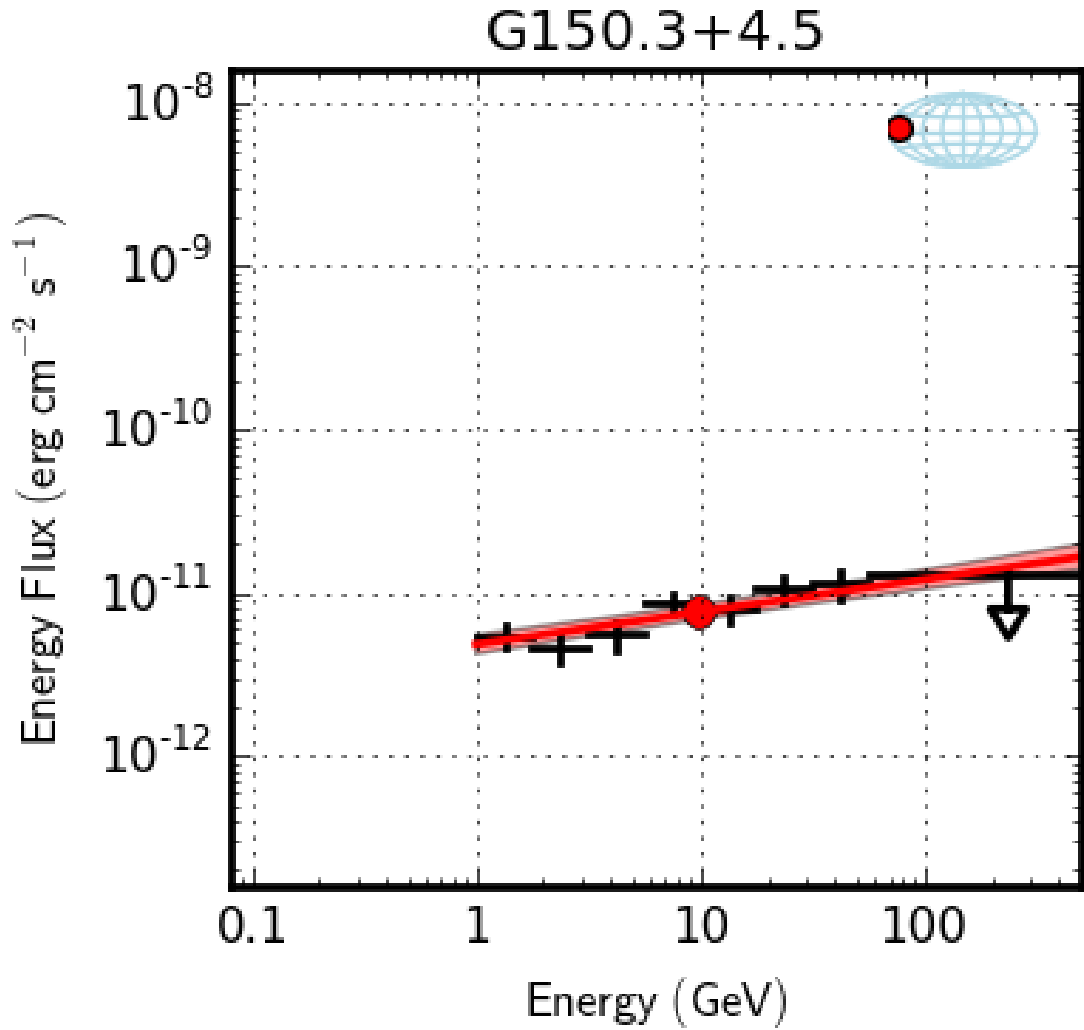


Figure 7.3: Spectral energy distribution for the extended source coincident with SNR SNR G150.3+4.5. [JAM: replace with gtlike SED when I have it]

### 7.4.3 X-ray

No diffuse nonthermal X-ray emission observed by ROSAT. No point sources near the center? Should a pulsar even be near the center? How to quantify this? Can we place a limit on ambient density with an upper limit on thermal X-ray emission? Magnetic field with nonthermal?

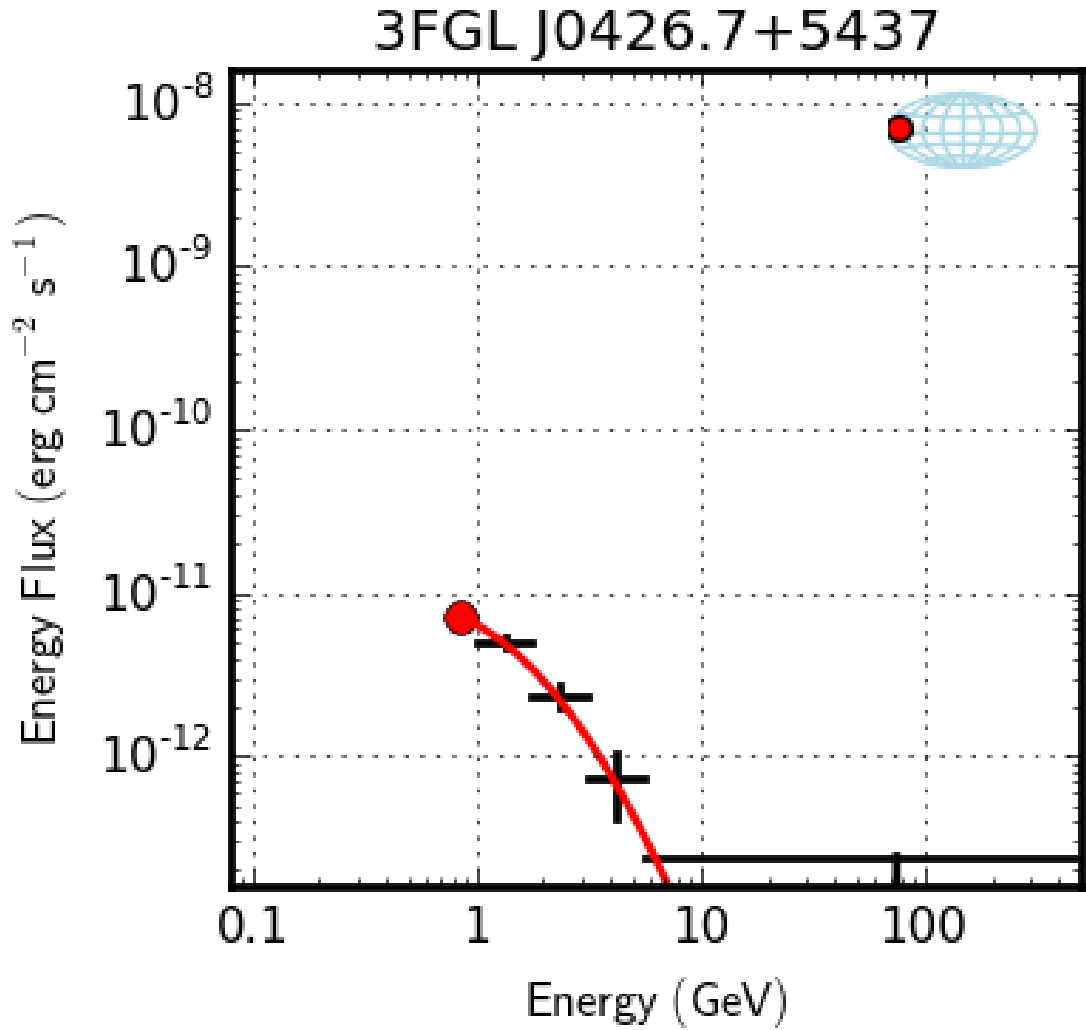


Figure 7.4: Spectral energy distribution of 3FGL J0426.. [JAM: replace with gtlike SED when I have it]

## 7.5 Discussion and Results

### 7.5.1 What is it?

Size + HI suggest that near distance corresponding to different HI velocities suggest it's aged, spectrum looks more like young SNR (hard + no GeV break ). Is it a weird young remnant or weird aged one? Leptonic dominated if young, hadronic

dominated if older? Something about nearby dense clouds masking hadronic emission? Maybe this is only true for MeV cosmic rays that are screened out though and it would only mask the pion bump, but not this higher energy emission?

PWN or SNR. Can we rule out PWN? See W41 paper, MSH 11-61A, Fabios recent G326 work (no, he just tries to use the PSF types and testing different model templates to try to disentangle SNR from PWN)?

No PSR candidate near center (should it be near the center? Depends on age) Is there some limit we can place on the PWN based on not seeing the pulsar? Like on Edot? OR something like Mattana et al. 2009 correlation between  $\text{flux}_x/\text{flux}_g \propto \text{Edot}$ ?

Assume it's in Sedov phase based on size + near distance, and calculate age, upper limit on Edot base on lack of x-ray flux? Or maybe if I assume the sources is the PWN and GeV radius is PWN radius, then can I estimate Edot based on size and evolution inside SNR?

If we assume close distance, age is only  $\approx 5\text{kyr}$ , maybe this is a transitional SNR? What do others like this look like? Puppis A? Gamma Cygni is a similar age too.something

## 7.5.2 Distance Considerations

probably doesn't need to be a different section.

### **7.5.3 Nonthermal Modeling**

I think I could get a working model with naima running pretty quickly, is it worth it?

## **7.6 Conclusions**



# Chapter 8

## SNR-MC, 10 GeV, and anything else?

Not sure how this is going to factor in yet. supernova remnant molecular cloud system (SNR-MC) should fit in somehow since a good deal of work was done? Less certain about 10gev.

Maybe this should say something about how the work I've done has contributed to the field of knowledge but also can lead to future work?

# Chapter 9

## Conclusions

Finally!

# List of Symbols and Acronyms

**2FGL** Second Fermi LAT source catalog.

**2FHL** Second Catalog of Hard Fermi-LAT Sources.

**2PC** Second Fermi LAT catalog of Gamma-ray Pulsars.

**LAT** Large Area Telescope.

**PWN** pulsar wind nebula.

**RoI** region of interest.

**SNR** supernova remnant.

**SNR-MC** supernova remnant molecular cloud system.

**SNRcat** First Fermi-LAT supernova remnant catalog.

# Bibliography

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, *Science*, 325, 840
- Abdo, A. A., Ajello, M., Allafort, A., et al. 2013, *ApJS*, 208, 17
- Abramowski, A., Acero, F., Aharonian, F., et al. 2011, *A&A*, 533, A103
- Abramowski, A., Aharonian, F., Ait Benkhali, F., et al. 2015a, *A&A*, 574, A27
- . 2015b, *A&A*, 574, A27
- Acero, F., Ackermann, M., Ajello, M., et al. 2013, *ApJ*, 773, 77
- . 2015, *ArXiv:1501.02003*, *arXiv:1501.02003:1501.02003*
- Ackermann, M., Ajello, M., Albert, A., et al. 2012, *ApJS*, 203, 4
- Ackermann, M., Ajello, M., Atwood, W. B., et al. 2016, *ApJS*, 222, 5
- Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, *A&A*, 456, 245
- Aharonian, F., Akhperjanian, A. G., de Almeida, U. B., et al. 2009, *ApJ*, 692, 1500
- Atwood, W., Albert, A., Baldini, L., et al. 2013a, *ArXiv:1303.3514*, *arXiv:1303.3514*
- Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, *ApJ*, 697, 1071
- Atwood, W. B., Baldini, L., Bregeon, J., et al. 2013b, *ApJ*, 774, 76
- Barr, E. D., Guillemot, L., Champion, D. J., et al. 2013, *MNRAS*, 429, 1633
- Gao, X. Y., & Han, J. L. 2014, *A&A*, 567, A59
- Gotthelf, E. V., & Halpern, J. P. 2008, *ApJ*, 681, 515
- Hewitt, J. W., Acero, F., Brandt, T. J., et al. 2013, *ArXiv e-prints:1307.6570*, *arXiv:1307.6570*

- Hewitt, J. W., & Fermi-LAT Collaboration. 2015, in American Astronomical Society Meeting Abstracts, Vol. 225, American Astronomical Society Meeting Abstracts, 140.31
- Kerr, M. 2010, PhD thesis, University of Washington, arXiv:1101.6072
- Lande, J., Ackermann, M., Allafort, A., et al. 2012, ApJ, 756, 5
- Lemoine-Goumard, M., Renaud, M., Vink, J., et al. 2012, A&A, 545, A28
- Lemoine-Goumard, M., Zavlin, V. E., Grondin, M.-H., et al. 2011, A&A, 533, A102
- Roberts, M. S. E., Romani, R. W., Johnston, S., & Green, A. J. 1999, ApJ, 515, 712
- Rosado, M., Ambrocio-Cruz, P., Le Coarer, E., & Marcelin, M. 1996, A&A, 315, 243
- Sollerman, J., Ghavamian, P., Lundqvist, P., & Smith, R. C. 2003, A&A, 407, 249