Abstract

Title of Dissertation:	γ -Ray Studies of Stellar Graveyards: Fermi-LAT Observations of Supernova Remnants and Extended Emission
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Here I shall abstract!

γ -Ray Studies of Stellar Graveyards: Fermi-LAT Observations of Supernova Remnants and Extended Emission

by

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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 because I'm not a degenerate.

Contents

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Chapter 1

Introduction

"Maybe I'll have a super relevant quote here!"

—by some awesome human, from *Some book*

1.1 Goooo γ-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.

Higher energy studies with the LAT have been my focus since the beginning. Talk about what's nice about staying above 1 GeV, 10 GeV, 50 GeV.

GeV TeV connection for 2FHL

Radio GeV for SNR cat (traces same particle population)

The advent of the LATpresents for the first time the capability to spectrally and spatially resolve SNR at GeVenergies.

it is uniquely situated to address these issues

egret was mostly pointed observation instrumented that would sometimes dwell on a spot for a couple of weeks, had a smaller field o view, didn't get as many photons (the LAT saw the entire EGRET sky in some short amount of time)

SNRsas sources of relativistic particles

Despite being the prime energy range to observe the effects of cosmic particle acceleration, the photon spectral energy distribution (SED) resulting from these overlapping emission channels are often difficult to spectrally distinguish from one another. [JAM: what's the point of this last sentence here? maybe no need to mention this now, i really just want to motivate GeV energies]

when talking about Energetic Gamma-Ray Experiment Telescope (EGRET)

Thompson et al. (1993) gives the 68% containment radius as $\theta \leq 5.85°(E_\gamma/100\,\mathrm{MeV})^{-0.534}$

1.2 I Think I Hate Most of the Section Titles :(

1.3 Maybe None of the Chapters Need Introductions?

1.4 Dissertation Overview

Chapter 2

Supernova Remnants: Theory and Observation

2.1 Introduction

Why study SNRs, what they are, history of SNR, radio detections,

2.2 Formation and Evolution

-Stars die and explode, that energy is very quickly put into the surroundings

-snowplough, ST, radiative,

- what else?

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

2.3   Morphology and Classification

SNRs characterized by morphology and evolution properties

shell type, mixed morphology, filled center composite)

Since I eventually do these all plane surveys, what does the spatial distribution of them at radio look like?

Not sure how much to say about radio observations, x-ray, TeV

2.4   Cosmic Ray SNR connection

Give the whole, if 10% of energy of SN explosion goes into particle acceleration, we can explain cosmic rays

Particle acceleration and DSA

This leads to gamma-ray section

2.5   Summary

In this section we summarized the end phase of stellar evolution (just enough to motivate SNRs) and descried the environs surrounding the supernova; development and phases of SNRs (and PWNe?). In particular we detailed the nonthermal emission mechanisms that produce γ -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 γ -rays. γ -ray spectral and morphological features. Trends across the population wrt spectral shape/breaks, higher luminosity for interacting rems. Cosmic rays, using gamma-rays to probe CR population. So much of γ -ray astro is really about studying CRs,

how much to say about them?

2.6 Scratch

This chapter needs a different title. It's more focused on the specific sources being studied in this thesis. Galactic extended sources, SNRs, PWNe, but as in the SNRcat, not just extended SNRs, point-like SNRs as well.

Less focus on PWNe. Only give as much as I feel I need to support mentioning them a bit for 2FHL?

The focus of this section is supernova remnants in a gamma-ray context. Theory of evolution, what the gamma-ray emission is like, what we can learn from them individually. This leads to the 1st SNR cat section for what we can do with them ensemble

NOt sure I really need any PWN stuff yet

in 2FHL we detect some pwn. 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 (composite means SNR + PWN) Maybe relevant for G150? Some things about interaction of reverse shock with PWN and crushing/reverberations of the PWN?

Montmerle (1979)

Chapter 3

Gamma-ray Astronomy

3.1 Introduction

Maybe this is not just gamma astro, but gamma astro of SNRS

The story of γ-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 α and β radiation, γ-ray's are the highest named energy of light

more historical context instead of a separate section

what is a gamma-ray

why bother studying gamma-rays

probe of extreme environments

thermal means follows maxwellian (maxwell-Boltzman) distribution

3.2 γ-ray Emission Mechanisms

Gamma-rays as a probe of cosmic rays and cosmic acceleration processes

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

Cosmic particle accelerators and γ-ray's accelerator plus target often

What's a CR, quick, general CR properties that are relevant to SNRs

why use gamma's to study CR

gamma-ray production mechanisms

myriad of gamma-ray generating mechanisms operate at this energy, so it's sometimes the only range that we can observe this emission in:

-Synch, -Bremss, -IC, -pi0,

3.3 Sources of γ-ray's

Maybe don't need this? The reason to is to say SNRs early on. Would I mention other sources to be complete?

SNRs as the primary source of Galactic CRs, order of mag (zwicky?) energy from 0.1*E SNR could account for energy in CRs in Galaxy

3.4 γ-ray Detection

Quick rehash of method of detecting γ-ray's? Or is this just about previous γ-ray detectors and the state of the γ-ray sky pre-Fermi? mention telescopes up to EGRET, bit of detail on EGRET and what the pre-Fermi γ-ray sky looked like, in particular in the context of SNRs, PWN, Galactic plane

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

One of the primary goals of fermi was to identify these sources and the site of CR acceleration. But also to uniquely open this high energy window that where no other telescopes really operated Brief history of radio detection of SNRs. detection at other wavelengths. what we see at γ -rays?

Motivation for why to study them (Sturner & Dermer 1995) (Esposito et al. 1996)

3.5 Scratch

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

Chapter 4

The *Fermi* Gamma-Ray Space Telescope and γ-ray Data Analysis

4.1 Introduction

The *Fermi* Gamma-Ray Space Telescope (*Fermi* hereafter), successor to the EGRET instrument on Compton Gamma-Ray Observatory (CGRO), was successfully launched into orbit around Earth on June 11 2008. *Fermi* consists of two instruments, the LAT and the Gamma-ray Burst Monitor (GBM).

The LAT, which is the primary instrument on *Fermi*, is a pair conversion telescope designed to detect photons from 20 MeV to greater than 1 TeV. Its standard mode of operation is a sky-survey mode in which it observes the entire sky every 3 hours. The GBM is designed to detect gamma-ray bursts (GRBs) in a waveband overlapping that of the LAT, and complementary in lowering that energy range. It is comprised of two types of scintillator detectors: two bismuth germanate crystals that operate from 150 keV to 30 MeV, and 12 sodium iodide crystals sensitive to photons between 8 keV and 1 MeV.

Combined the LAT and GBM make up a formidable observatory, spanning more than 8 decades in energy, and is currently the only instrument performing all-sky observation in this broad energy range. [JAM: maybe I don't need any gbm stuff? I mentioned it just to be complete about what fermi is, probably won't mention it again, and this last par doesn't really flow into the next]

4.2   The Large Area Telescope

The need for Fermi in the context of what EGRET did

What were open questions from EGRET era, state of γ-ray detection of SNRs, what question was Fermi deigned to answe

Description of the instrument [JAM: not sure this really goes here, separate section for what questions Fermi was designed to answer?]

track and reconstruct the path of Describe it's objectives and strengths over predecessors Details on the LAT and it's design, be sure to focus on things that particularly pertinent 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

4.3 γ-ray Data Analysis

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

Section on diffuse emission

4.3.1 Do I need subsections?

4.4 Scratch

point spread function (PSF)

I'm not sure about this chapter yet. Maybe it's a general section on Analysis of Fermi data,

Chapter 5

Revealing the GeV Supernova

Remnant Population

5.1 Supernova Remnants at γ-ray Energies

By the end of the its science run, EGRET had detected 271 sources above 100 MeV, within a minimum detection significance of 4σ, 170 of which had no clear multi-wavelength counterpart, with 81 of those unidentified lying within $|b| < 10°$ of the Galactic plane (Hartman et al. 1999). The main hindrances to source identification were the numerous potential source counterparts (the EGRET PSF was energy dependent, with a 68% containment radius of $\sim 6°$ at 100 MeV and smaller for higher energies) and the large EGRET error boxes. In addition to this, the primary method for identifying a γ-ray source as an SNR is through a compatible angular extent with observations at some other wavelength, thus the ability to resolve emission from an SNR is vital to understanding the mechanisms therein giving rise to γ-rays. Figure 5.1 shows an EGRET all-sky map at $E > 100$ MeV where the preponderance of unidentified sources and locations thereof are made clear.
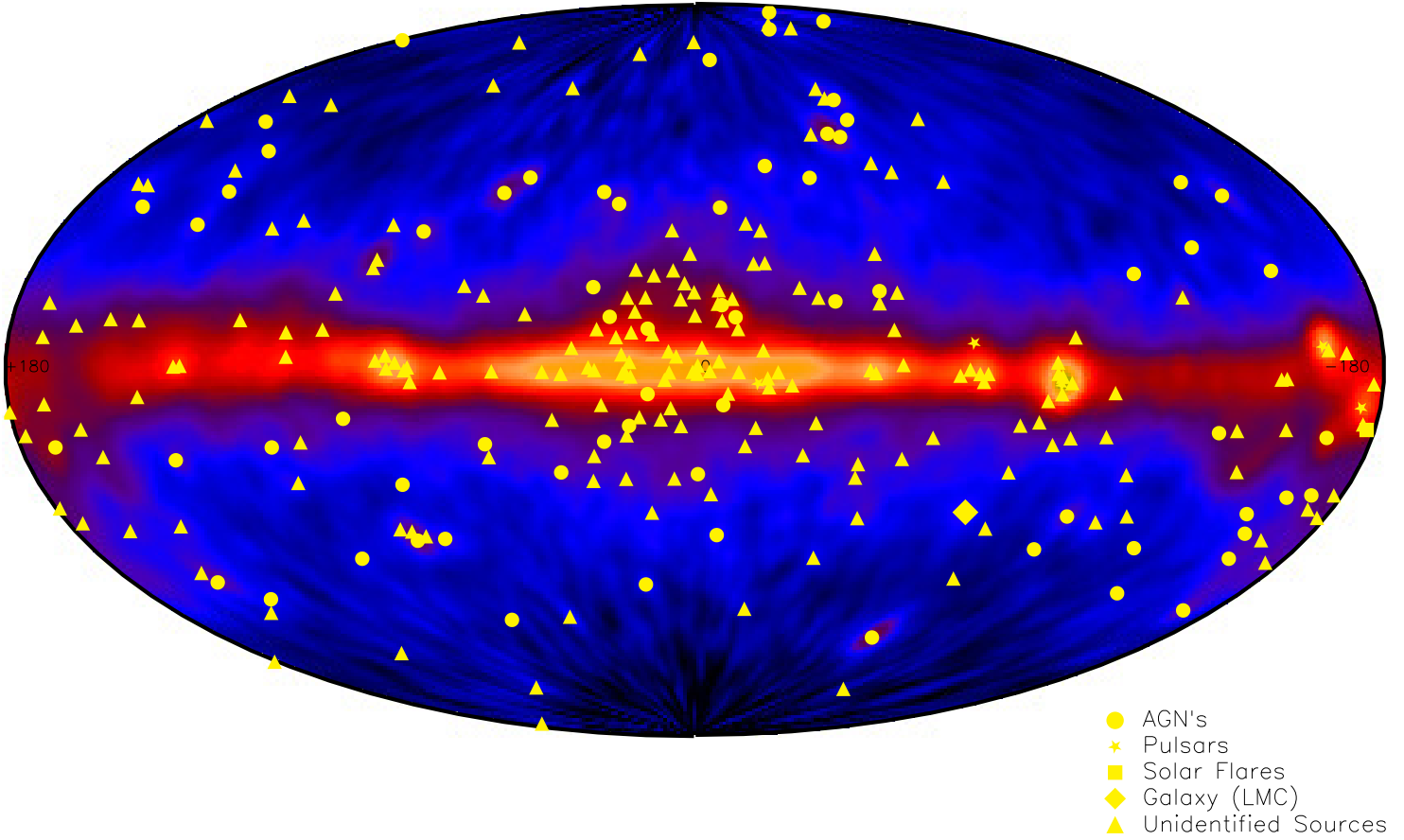
Figure 5.1: Third EGRET catalog all-sky map. Unidentified sources represented by triangles. Image courtesy of `https://heasarc.gsfc.nasa.gov/docs/cgro/images/epo/gallery/skymaps/`

In spite of the difficulties in EGRET source association, many studies have attempted correlating the unidentified EGRET sources with various Galactic populations. In particular, several authors found strong evidence for statistical correlation between SNRs and some of the low-latitude unidentified sources (Esposito et al. 1996; Romero et al. 1999; Sturner & Dermer 1995). In a review of the state of potential SNR / EGRET associations, Torres et al. (2003) showed that there were 19 unidentified EGRET sources that had an SNR fall within its 95% error box. Performing Monte Carlo simulations of the population of EGRET sources, they determined that the chance probability for the 19 sources to be coincident with an

SNR was 1.05×10^{-5}, implying a probability of 0.99998 that at least one of the associations is real. Despite the statistical correlation of EGRET sources with SNRs, there were no definitive associations of an SNR with any EGRET sources.

As the successor to EGRET, the LAT was designed to improve upon its predecessor in a multitude of areas relevant to detecting SNRs (Ackermann et al. 2012; Atwood et al. 2009). The LAT has a much improved angular resolution (68% single-photon containment radius $\sim 0.4°$ at 1 GeV for photons with the best quality direction reconstruction, PSF3 event type, compared to $\sim 1.7°$ for EGRET at the same energy), necessary to resolve SNRs as extended objects. The LAT also benefits from a superior sensitivity due to a combination of the improved PSF, larger peak effective area (> 9000 cm^2 vs. ~ 1500 cm^2), wider field of view (FoV) (2.4 sr, which is nearly 5 times that of EGRET), and deeper, more-uniform sky exposure (afforded by the LAT's scanning observations as opposed to EGRET's pointing operation).

This bump in sensitivity results in the LAT detecting considerably more sources than EGRET. Remarkably, within its first three months of commission, the LAT detected 205 sources (above 10σ significance (Abdo 2009)), and by 11 months, 1451 sources above 4σ (Abdo et al. 2010), compared to the aforementioned 271 over the entire EGRET mission. In fact, over its lifetime, EGRET detected a total of about 1.5×10^6 cosmic photons, while as of March 2016, the LAT has detected $\sim 863 \times 10^6$ source class photons. The LAT's point-source sensitivity peaks between 1 and 10 GeV, depending on location on the sky. [JAM: plot comparing lat to egret sensitivity?]. With its increased sensitivity and higher energy range (up to ~ 2 TeV with the recent Pass 8 event reconstruction improvements, which is nearly an order of magnitude higher than EGRET), the LAT is uniquely situated to study the γ-ray morphology and spectra of SNRs.

Both energetic lepton interactions (i.e.inverse compton (IC) radiation of relativis-

tic electrons interacting with ambient photon fields, and nonthermal bremsstrahlung) and hadronic processes (π_0 decay γ-rays from cosmic ray (CR) protons encountering surrounding nuclei) produce spectra observable at γ-ray energies (see Chapter 3 for details). While the IC generating electron population is also observable through emission of radio synchrotron photons, the proton-proton interaction solely emits γ-rays. Despite being the prime energy range to observe the effects of cosmic particle acceleration, complexities at the lower LAT energy range stymie SNR morphology studies.

The LAT detects a strong, soft band of diffuse emission in the Galactic plane due to the interactions of CRs with interstellar material. This bright diffuse radiation combined with the multiple potential emission scenarios, broadening PSF at decreasing energy, and a high source density in the plane can make it difficult to spatially disentangle sources observed by the LAT. To circumvent these difficulties, the majority of the analyses undertaken in this thesis are focused on the $E \geq 1$ GeV energy range. This energy band is ideal for probing the properties of the accelerated particle populations present in the SNR environment. Studies of SNRs above 1 GeV benefit from finer LAT PSF, striking a balance between minimizing the diffuse contribution, maximizing photon sensitivity, and retaining good photon statistics. Furthermore, evolved SNRs exhibit a spectral break between 1-10 GeV. Explanations for the break range from Alfvén wave evanescence generated by collisions of partially ionized material in molecular clouds (MCs) overtaken by SNR shocks (Malkov et al. 2011), reflected shocks in clouds Inoue et al. (2010), and energy-dependent diffusion from shocks Ohira et al. (2011). Studying SNRs in this energy range hones our capability to tackle several goals set out by the *Fermi* team when the mission was conceived.

Two of the primary science goals of the LAT are to 1. resolve the γ-ray sky,

uncovering the nature of the unidentified sources detected by EGRET, and 2. to understand the mechanisms of cosmic particle acceleration (Atwood et al. 2009). In this chapter, we describe our efforts towards addressing these questions by studying the γ-ray emission coincident with sources comprising the population of known radio emitting SNRs.

Prior to this work, several individual studies with the LAT had successfully resolved spatially extended emission from SNRs (Acero et al. 2015, and references therein), yet no systematic analysis leveraging the LAT's full-sky coverage had yet been attempted. We performed for the first time a uniform study of the SNRs in aggregate to measure the properties common to these objects. An understanding of these common characteristics allows us to assess SNRs as a class of γ-ray and CR emitting objects and serves as the impetus for this uniform analysis of the known Galactic SNRs. We report here on the published results from the First *Fermi*-LAT Supernova Remnant Catalog (SNRcat) Ackermann et al. (2015). [JAM: they aren't published yet, but almost. Maybe that will change by June]

[JAM: 2FGL only had 7 ID'd SNR, 4 snr, 58 spp. 3FGL had 12 SNR, 11 snr, 49 spp. I'm not sure what made some snr vs. spp. They must have all been point sources right? No known radio pwn, psr?]

5.2 The `pointlike` Maximum-Likelihood Package

As described in Chapter 4, maximum-likelihood analysis is the ideal method for determining the properties of LAT-observed sources due to the "counting-experiment" nature of *Fermi*-LAT. The standard maximum-likelihood tools for analyzing LAT data are implemented via the *Fermi* Science Tools, and in particular `gtlike`. Despite being the optimum method, likelihood analysis of LAT data is complex due

to the highly non-linear performance of the instrument and can be computation-ally expensive. It is necessary to manage the data and response of the telescope as well as the source and background models. Furthermore, due to the broadening of the PSF at low energies, even when studying a single source, it is necessary to include in the model descriptions of multiple surrounding sources. The `pointlike` binned maximum likelihood package was created to ameliorate some of these issues. Described in detail in Kerr (2010), `pointlike` is an alternate likelihood analysis framework, designed to be interactive and rapidly evaluate likelihoods. It is ideally suited for large-scale studies (e.g. all-sky analysis like the LAT point source cata-logs), and ones requiring several iterations (e.g. source finding and localization, TS map creation [JAM: assume I've mentioned TS maps already]).

There are several ways in which `pointlike` improves in efficiency compared to the Science Tools. It saves computational time, while sacrificing accuracy with several assumptions and approximations to integrals, such as the PSF not varying strongly with photon incidence angle (allowing a single PSF for each individual bin), sources are stationary in time bins [JAM: more herE?]. Most importantly though importantly, `pointlike` varies the size of spatially binned `HEALPix` pixels (Górski et al. 2005) according to energy. The PSF at lower energies is large and can contain many counts, while at higher energies, the PSF shrinks and many pixels will not contain even a single count. `pointlike` creates `HEALPix` bins that are approximately the size of the PSF at a given energy, and disregards empty bins to speed up the likelihood calculation.

Next, get into Josh's extension additions to pointlike It accomplishes this by binning the sky in

Another assumption to speed things up is that the PSF doesn't vary too much with event incidence angle in individual bins. To ensure this even more, events with

17

a reconstructed angle ¿ 66.4deg (cos theta = 0.4) are removed (idk why this angle)

This section is about the tools (and intricacies there in) developed to study SNRs with Fermi

Describe pointlike and what problems it aims to solve in contrast to gtlike.

pointlike is good at analysis where iteration is key because it takes some shortcuts with some integrals and is faster than gtlike.

Not sure how much to talk about pointlike here vs. modifiying what's in the next chapter from the snrcat paper.

The addSrcs framework extends/exploits pointlike

addSrcs in this section or merged into the next one?

I need to stress that this is not just a tool developed, but there's an art and finesse to it (talk about the problems we overcame), there was much iteration.

tool plus knowledge to get the best result

what are the aspects of addSrcs tht needed knowhow, finagling

[JAM: the following is from a confluence page motivating and describing addSrcs]

To attain the best understanding of a source of interest, the best characterization of the corresponding ROI is necessary. This is particularly challenging in dense source and strong diffuse dominated regions (i.e. the Galactic plane). We have developed an automated method for systematically locating and modeling all potential point and/or extended sources in an region of interest (RoI) using `pointlike`. This work started as a parallel and complementary analysis to the SNR cat pipeline, intended to minimize possible bias introduced by the initial model for an ROI (e.g 2FGL) It is used to derive the input sources model for the SNR catalog. The goal of this work is to use this "add sources" method to aid in characterization of GeV emission near SNRs and nearby molecular clouds.

what are some motivations for various addSrcs decisions

How to distinguish addSrcs from how addSrcs was applied to the SNR cat. For the SNRcat, it was addSrcs in PS mode with specifics relevant to the SNR cat needs (like what?)

Describe how we put together/designed this analysis what questions were we trying to answer?

tested pipeline with 6 sources (I have the tests somewhere, see old Fermi symp poster, Gal Evo too)

5.3 Input Source Model Construction

[JAM: add some more bkg on the SNR cat here and add more of the snrCat intro]

To characterize each candidate SNR we constructed a model of γ-ray emission in the RoI which includes all significant sources of emission as well as the residual background from CRs misclassified as γ-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)(Nolan et al. 2012), 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)(Abdo et al. 2013), 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 γ-ray emission and residual charged particles misclassified as γ-rays. Both the corresponding isotropic model, iso_p7v6source.txt, and the IEM are the same as used for the 2FGL catalog analysis[1].

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[1]Further details on the diffuse emission models are available at `http://fermi.gsfc.nasa.gov/`

Compared to 2FGL, we used an additional year of data and limited the energy range to $1 - 100\,\mathrm{GeV}$. This can result in different detection significances and localizations than previously reported in 2FGL. To account for these effects, we recreated the RoIs' inner $3°$ radius regions, which encompass the radio extents of all known SNRs, observed to be $\leq 2.6°$ and allows a margin for the LAT PSF. The weighted average 68% containment radius of the LAT PSF for events at $1\,\mathrm{GeV}$ is $\sim 0.7°$ (**?**). 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 $3°$ 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 (Abdo et al. 2013). 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 $3°$.

We generated a map of source test statistic (TS) defined in Mattox et al. (1996) via `pointlike` on a square grid with $0.1° \times 0.1°$ spacing that covers the entire RoI. `pointlike` 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., $\mathrm{TS} = 2\log(\mathcal{L}_1/\mathcal{L}_0)$. At the position of the maximum TS value, we added a new point source with a Power Law (PL) spectral model:

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

where N is the integrated photon flux, Γ is the photon index, and $E_{\min}$ and $E_{\max}$ are

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`ssc/data/access/lat/BackgroundModels.html`

the lower and upper limit of the energy range in the fit, set to $1\,\mathrm{GeV}$ and $100\,\mathrm{GeV}$, respectively. We then performed a maximum likelihood fit of the RoI to determine N and Γ and localized the newly added source. The significance of a point source with a PL spectral model is determined by the χ_n^2 distribution for n additional degrees of freedom for the additional point source, which is typically slightly less than $\sqrt{\mathrm{TS}}$[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 $5°$ of the RoI center, including identified AGN and pulsars. For 2FGL sources between $5°$ and $10°$, 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 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 $\mathrm{TS_{bandfits}}$. A value for $\mathrm{TS_{bandfits}}$ much greater than the TS calculated with a PL ($\mathrm{TS_{PL}}$) suggests with a more rapid calculation that the PL model may not accurately describe the source. Analogously to 2FGL (Nolan et al. 2012), we allow for deviations of source spectra from a PL form by modeling sources with a log-normal model known

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[2]See http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/ Cicerone_Likelihood/TS_Maps.html for further details.

colloquially as LogParabola or logP:

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

where N_0 is the normalization in units of photons/MeV, α and β define the curved spectrum, and E_b is fixed to $2\,\mathrm{GeV}$. If $\mathrm{TS_{bandfits}} - \mathrm{TS_{PL}} \geq 25$, 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: $\mathrm{TS_{curve}} \equiv 2(\log \mathcal{L}_{\mathrm{logP}} - \log \mathcal{L}_{\mathrm{PL}}) \geq 16$. 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 $\mathrm{TS} < 16$ for three consecutively added new sources, denoted as $\mathrm{N_{TS<16}} = 3$. 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 $\mathrm{N_{TS<16}} = 3$ was chosen to avoid missing sources with $\mathrm{TS} \geq 25$, 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 $\mathrm{N_{TS<16}} = 6$ and counted how many $\mathrm{TS} \geq 25$ 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° and 5° of the center of the RoI, just its normalization was freed, and if greater than 5° 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° of a γ-ray pulsar and refit the pulsar in the $1 - 100\,\text{GeV}$ range following the 2PC conventions. 2PC modeled pulsar spectra as PL with an exponential cutoff (PLEC),

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

where N_0 is the normalization factor, Γ 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 $\text{TS}_b \equiv 2(\log\mathcal{L}_{\text{PLEC}} - \log\mathcal{L}_{\text{PLEC1}})$ to determine which to use. If $\text{TS}_{\text{cut}} < 9$ is reported for the pulsar in 2PC then a PL model is used. If $\text{TS}_{cut} \geq 9$, we then check to see if the cutoff energy fit in 2PC lies within the restricted energy range of $1 - 100\,\text{GeV}$ used in this work. For pulsars with cutoffs $\geq 1\,\text{GeV}$, we then use the PLEC model if $\text{TS}_b \geq 9$, 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 **??**.

5.4 Comparison of Source Models with 2FGL

This SNR catalog was constructed using 3 years of P7 Source class data in the energy range $1 - 100\,\mathrm{GeV}$, whereas 2FGL used 2 years of data over the larger energy range $0.1 - 100\,\mathrm{GeV}$. 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 **??**, 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° 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 5.2 and 5.3 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 5.2, the number of sources in the derived input model is typically greater than the number of 2FGL sources that are significant at $1 - 100\,\mathrm{GeV}$. 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 $3°$ 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.
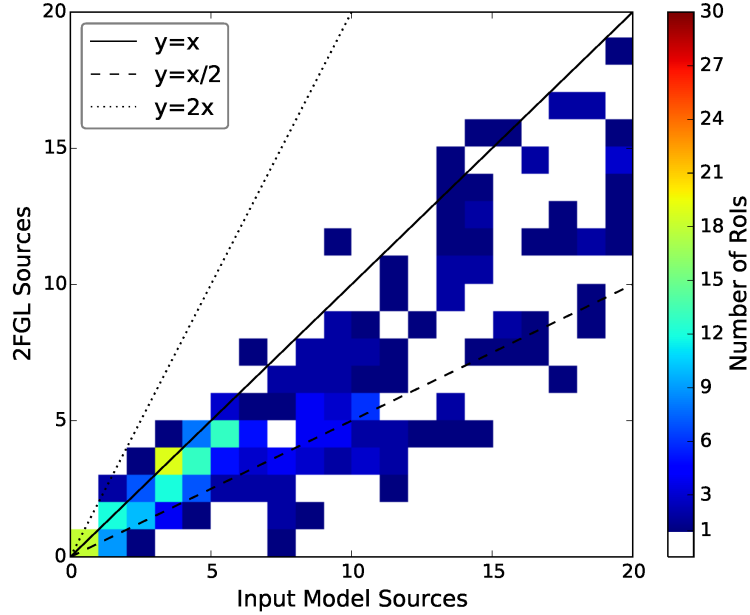
Figure 5.2: Comparison of the number of 2FGL sources with $\mathrm{TS}_{1-100\,\mathrm{GeV}} \geq 25$ (excluding AGN and pulsars) with the number of newly added input model sources in the present analysis, for sources within $3°$ of the center of each RoI. The color scale shows the number of RoIs with a particular combination of numbers of 2FGL sources and new sources. White corresponds to no RoI with that combination of source counts.

To more accurately represent the 2FGL sources being reproduced in the central

3°, in Figure 5.3 we limited the input model sources to those within 0.2° (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°. Given that in these same regions we have more new sources than 2FGL sources, as seen in Figure 5.2, 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 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° 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.

5.5   SNR Catalog Results

What to include from SNR cat

Pull parts of the intro/abstract as needed.

sections: 2, 2.1, 2.2, 2.3 (do I need 2.3.1, 2.3.2)

First par of 3.1 about how we classify. Summarize some of the relevant catalog results of section 3.2. There's no real reason to include the catalog tables I think.
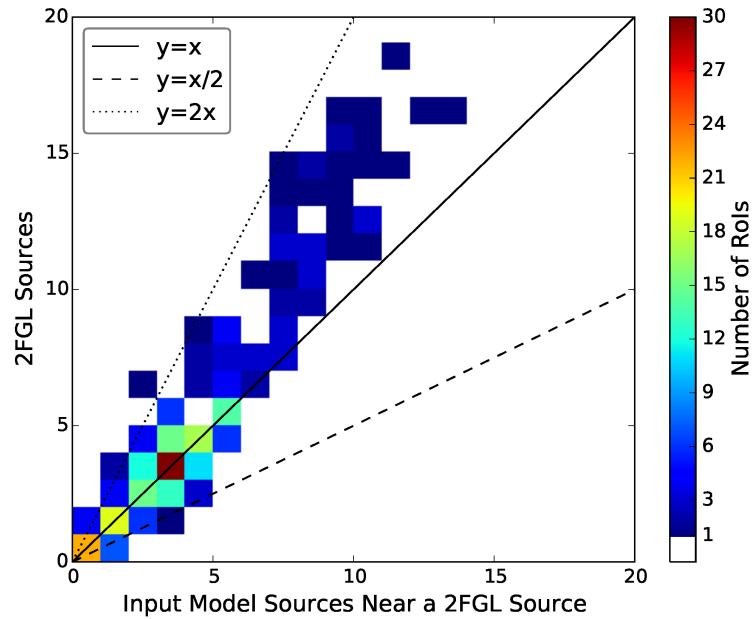
Figure 5.3: Same as Figure 5.2, including only input model sources lying within 0.2° of a 2FGL source.

Parts of 3.2.1 3.2.2, 3.2.3 just to highlight which sources were newly detected.

What to include from section 4? I didn't make these plots, but I contributed to the pipeline script and gave advice on things.

For the mock snrCatalog, I didn't do the analysis, but I ran addSrcs on the mock sources. maybe there's not much to say about this though.

Section 5? It's not my work, but I participated in discussions, edited text in the section a little bit. I think something needs to be included from this because one of the points of the paper was to see what we could say about the total energy in CR in the Galaxy

Parts of conclusion

Which figure to include from snr cat results?

5.6 Summary

In this chapter, we have presented results from the publication of the SNRcat. Application of addSrcs adding point sources to characterize emission in anRoI. 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?

With its unprecedented sensitivity and angular resolution above 1 GeV, the LAT provides for the first time the opportunity to distinguish SNR-emitted photons from their backgrounds, and to unambiguously detect and identify dozens of SNRs. [JAM: maybe this is for the intro/abstract because it's a little vague]

The LAT is uniquely situated to address these goals and definitively detect and identify dozens SNRs

Focus our efforts on

5.7 Scratch

has the spatial and spectral sensitivity to resolve

good spatial and spectral

talk about how much "power" comes from the higher energy range,

EGRET point source sensitivity is $\sim 1\text{x}10^{-7}$ cm^{-2} s^{-1} `http://fermi.gsfc.nasa.gov/science/instruments/table1-1.html` get this number from somewhere else

[JAM: somewhere I should also say that identifying an extended source as such gives better spectra, see 2FHL]

Thompson et al. (1993), egret observed a total of 1.5 million celestial γ-ray

[JAM: Fermi goals: 1. Resolve the γ-ray sky: the origins of diffuse emission and the nature of unidentified sources: Source identification through good source localization, measurement of spectra across broad energy range, nearly continuous monitoring of the sky for temporal variability 2. Understand the mechanisms of particle acceleration in celestial sources:]

[JAM: understanding accel plus identification of the potential SNRs motivates the SNR cat]

[JAM: snrs as source of Galactic cosmic rays, and thus as drivers of Galactic evolution]

-what's to gain from studyng the population vs individual?

-constraint on CR energy density in the Galaxy

-do the observed g-ray properties match those of models?

-like index etc?

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 $|b| < 10°$.

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.

Something about connecting to TeV

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 ≥ 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 $1.8\,\mathrm{GeV}$ to $30\,\mathrm{TeV}$. 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 ($|b| < 10°$) 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 $10°$, centered on $b = 0°$ with neighboring ROIs overlapping and separated by $5°$ in Galactic longitude. Our initial model of the γ-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 $14° \times 14°$ region.

A TS map, that included all significant sources found previously, made up of $0.1° \times 0.1°$ bins across the ROI, was created at each iteration and a small radius ($0.1°$) 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 $\mathrm{TS_{ext}} \geq 16$, where $\mathrm{TS_{ext}} = 2 \log(\mathcal{L}_{\mathrm{ext}}/\mathcal{L}_{\mathrm{ps}})$ (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 $\mathrm{TS_{ext}} < 16$, 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 LATpulsar 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 $TS_{ext} > TS_{2pts}$ (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 γ-ray emission in this region. However, the surrounding γ 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 $\sigma_{\mathrm{disk}} = 0.36°\pm 0.03°$, 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 γ-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 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 $r_{68,\mathrm{Gaussian}} = 1.51\sigma$, and $r_{68,\mathrm{disk}} = 0.82\sigma$ (Lande et al. 2012). We find that $r_{68} \simeq 0.30°$ for 2FHL J1419.2−6048e, and $r_{68} \simeq 0.09°$ for HESS J1420−607.

2FHL J1355.2−6430e, coincident with the VHE source HESS J1356−645, is detected as extended ($\sigma_{\mathrm{disk}} = 0.57° \pm 0.02°$) 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 ($\sigma_{\mathrm{Gauss}} < 0.39°$) 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 $r_{68} \simeq 0.47°$ for 2FHL J1355.2−6430e and $r_{68} \simeq 0.30°$ for HESS J1356−645.

2FHL J1112.4−6059e is an extended source ($\sigma_{\mathrm{disk}} = 0.53° \pm 0.03°$) 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 ($\sigma_{\mathrm{disk}} = 1.27° \pm 0.04°$), with a hard spectrum, that has not been previously detected at γ-ray energies. It overlaps the recently discovered radio SNR G150.3+4.5 (Gao & Han 2014). G150.3+4.5 is a $2.5° \times 3°$ (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 1σ 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 2FHLand 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}	ΔF_{50}	Γ	$\Delta\Gamma$	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.
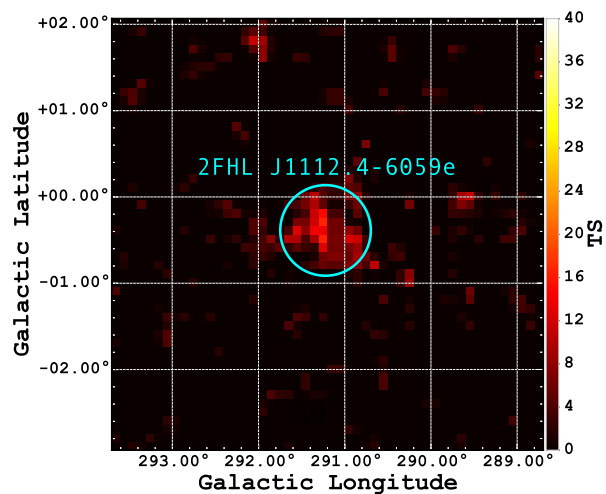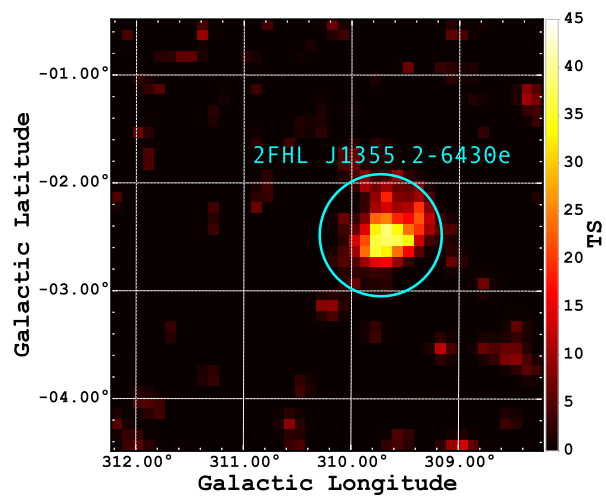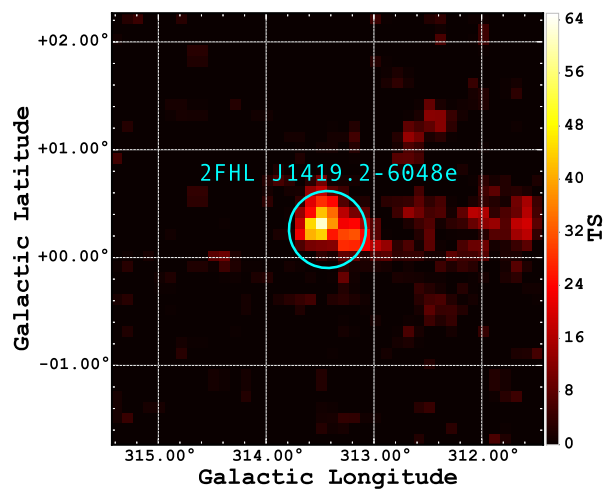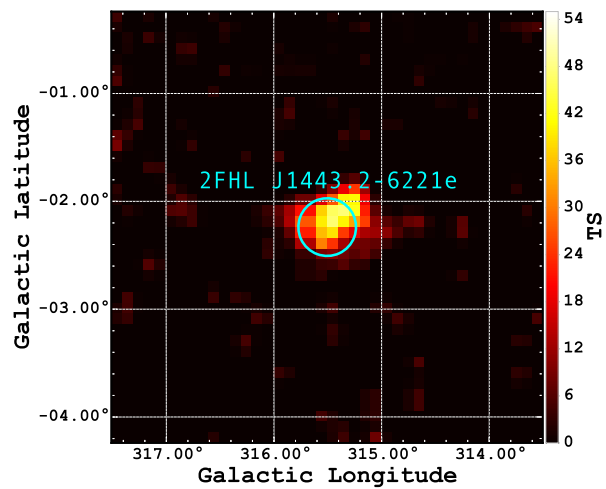
Chapter 7

SNR G150.3+4.5

Dedicated analysis of one interesting 2FHLresult. First blindly detected extended γ -ray source.

-Direct application of addSrcs to an intersting newly detected GeV SNR

-dedicated analysis of the one source to try to understand its nature

-It's interesting because :

-it was blindly detected

-might be the closest rem

-spectrum + index seems like dynamically young, but age and distance are hard to constrain, so it could be older

-Understanding this remnant contributes to the connection between Fermi and TeV telescopes

Take this all straight from the paper I write. Not sure how much more I'd need to add

7.1 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 §7.2, detail multiwavelength observations in §7.3, and discuss various emission origin scenarios in §7.4.

7.2 *Fermi*-LAT Observations and Analysis

7.2.1 Data Set and Reduction

Fermi-LATis a pair conversion telescope sensitive to high energy γ-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^2 above 1 GeV for on axis events and a 68% containment radius angular resolution of $\sim$0.8° 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°x14° region centered on SNR SNR G150.3+4.5 using the P8R2_SOURCE_V6 instrument response functions, with a pixel size of 0.1°. To reduce contamination from earth limb γ-rays, only events with zenith angle less than 100° were included.

For spectral and spatial analysis we utilized both the standard *Fermi*Science Tools (version 10-01-01)[1] , 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 γ-ray background)[2] 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° of the center of our region of interest (RoI). We replaced the position and spectrum of any 3FGL pulsars in the 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

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[1]`http://fermi.gsfc.nasa.gov/ssc/`

[2]`http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html`

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 automatially and iteraively 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 $5°$ 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, $\text{TS} = 2 \, \text{Log}(\mathcal{L}_1/\mathcal{L}_0)$ 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.

7.2.2 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 $0.6°$ 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 ~ 0.1 mJy. The source is located about $0.8°$ from the center of the SNR. We discuss this source and potential association with SNR G150.3+4.5 further in §7.4.2).

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 $\sigma = 0.1°$ 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); $\mathrm{TS}_{\mathrm{ext}} = 2 \log(\mathcal{L}_{\mathrm{ext}}/\mathcal{L}_{\mathrm{ps}})$, with $\mathcal{L}_{ext}$ being the likelihood of the model with the extended source and $\mathcal{L}_{ps}$ that with of a point source located at the peak of emission interior to the extended source. For the disk model, $\mathrm{TS}_{\mathrm{ext}} = 298$, with a best fit radius, $\sigma = 1.40° \pm 0.03°$ [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
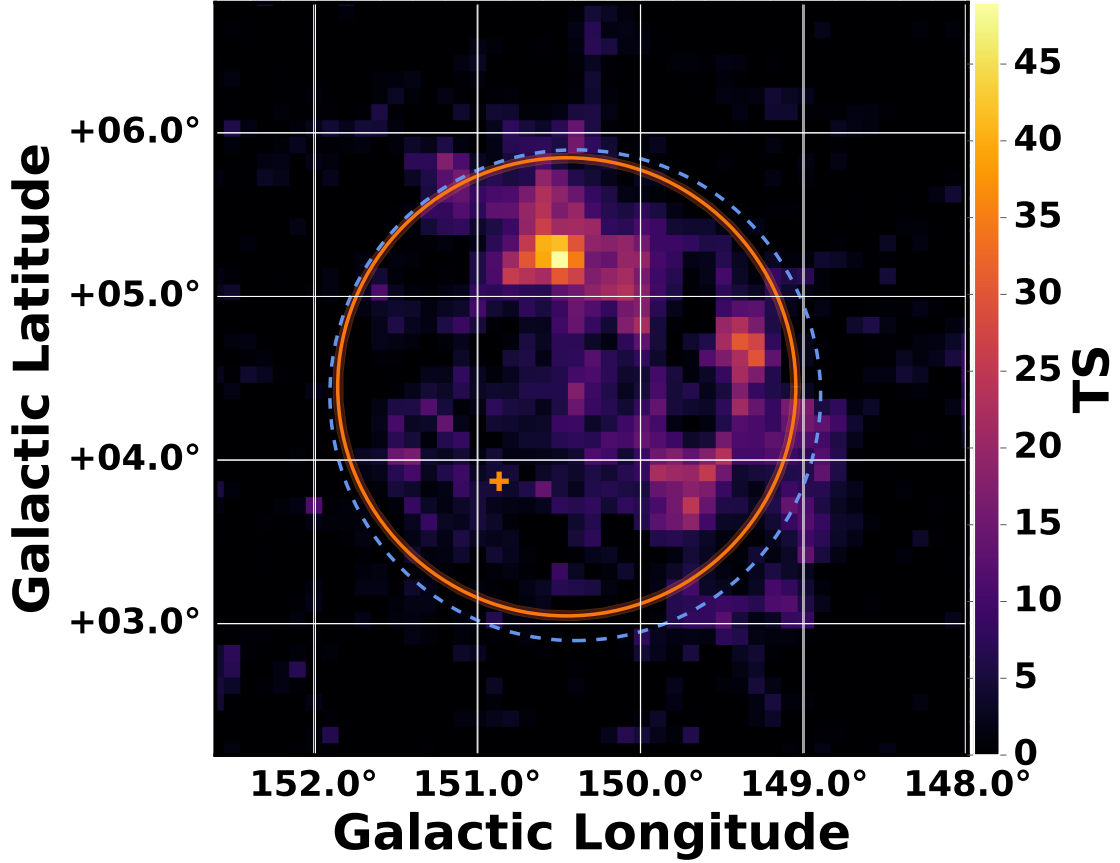
Figure 7.1: Background subtracted residual TS map above 1 GeV with 0.1°x 0.1° pixels for fixed index $\Gamma = 2$, centered on SNR SNR G150.3+4.5. The orange circle and translucent shading show the fit disk radius and 1σ errors, respectively, for the extended source, the orange cross shows the position of 3FGL J0426.7+5437 (included in the background model), and blue dashed circle is the extent of the radio SNR.

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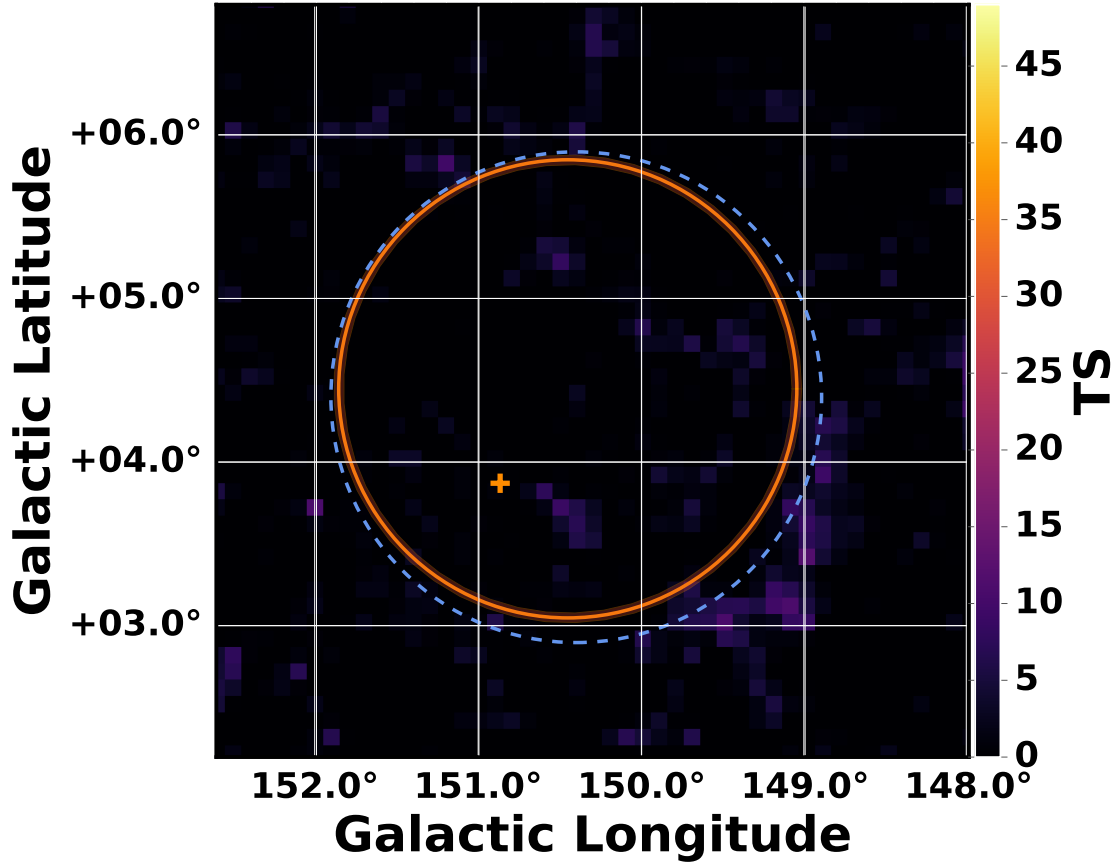
Figure 7.2: Same as Figure 7.1 but with disk in the background model [JAM: should this be a residual counts map instead?]

model at the 2.6σ level (ΔTS $= 9$ 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

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

Table 7.2.   New 2FHL extended sources

Spatial Model[a]	TS	TS$_{ext}$	σ ∘	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 compatison. 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?

[a]comments and notes?

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 intrisically 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.

7.2.3 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 $(7.17 \pm 0.73 \text{ x}10^{-11})$ erg cm^{-2} s^{-1}and TS = 373 [JAM: these are the point-like results, change them when I get the gtlike res]. We tested the γ-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 (ΔTS ~ 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

7.3 Multiwavelength Observations and Analysis
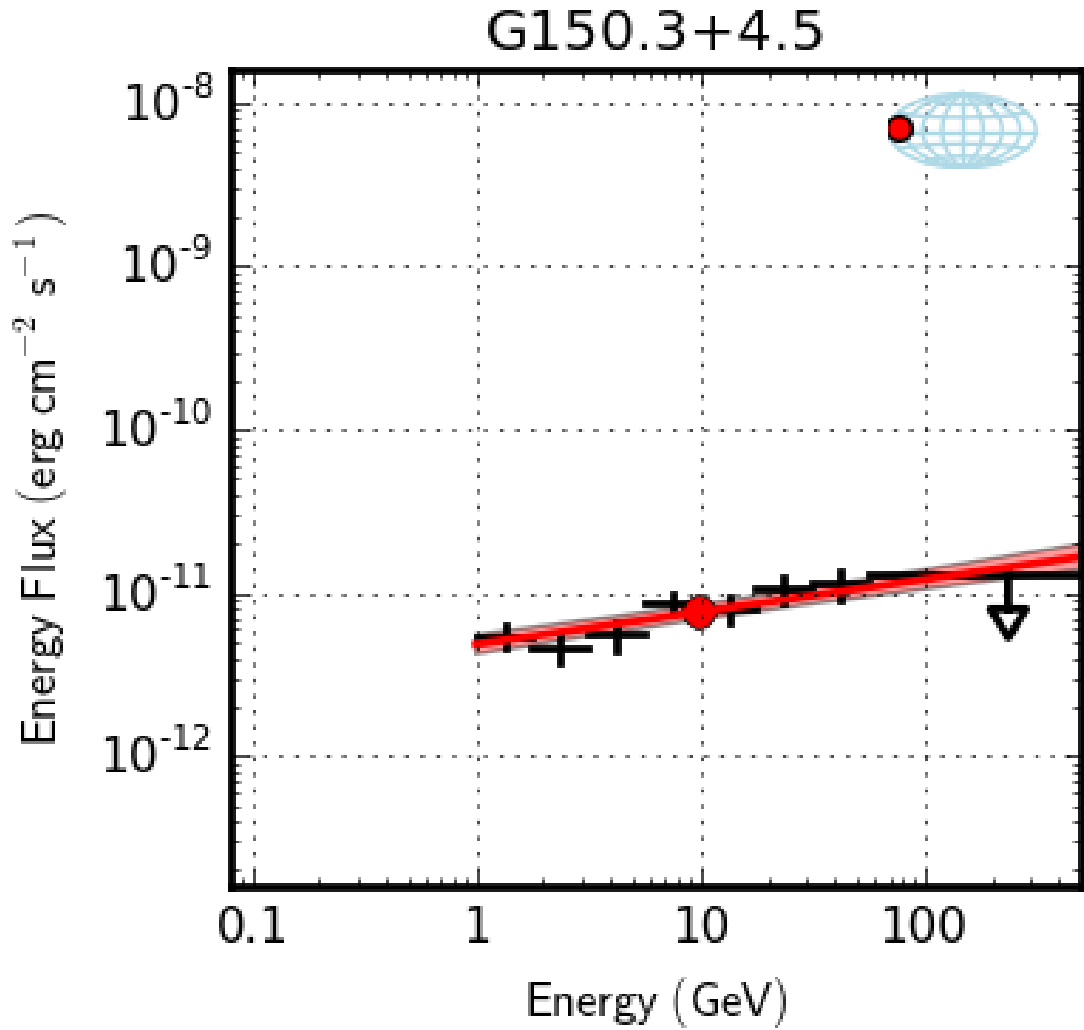
7.3.1 HI

7.3.2 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]

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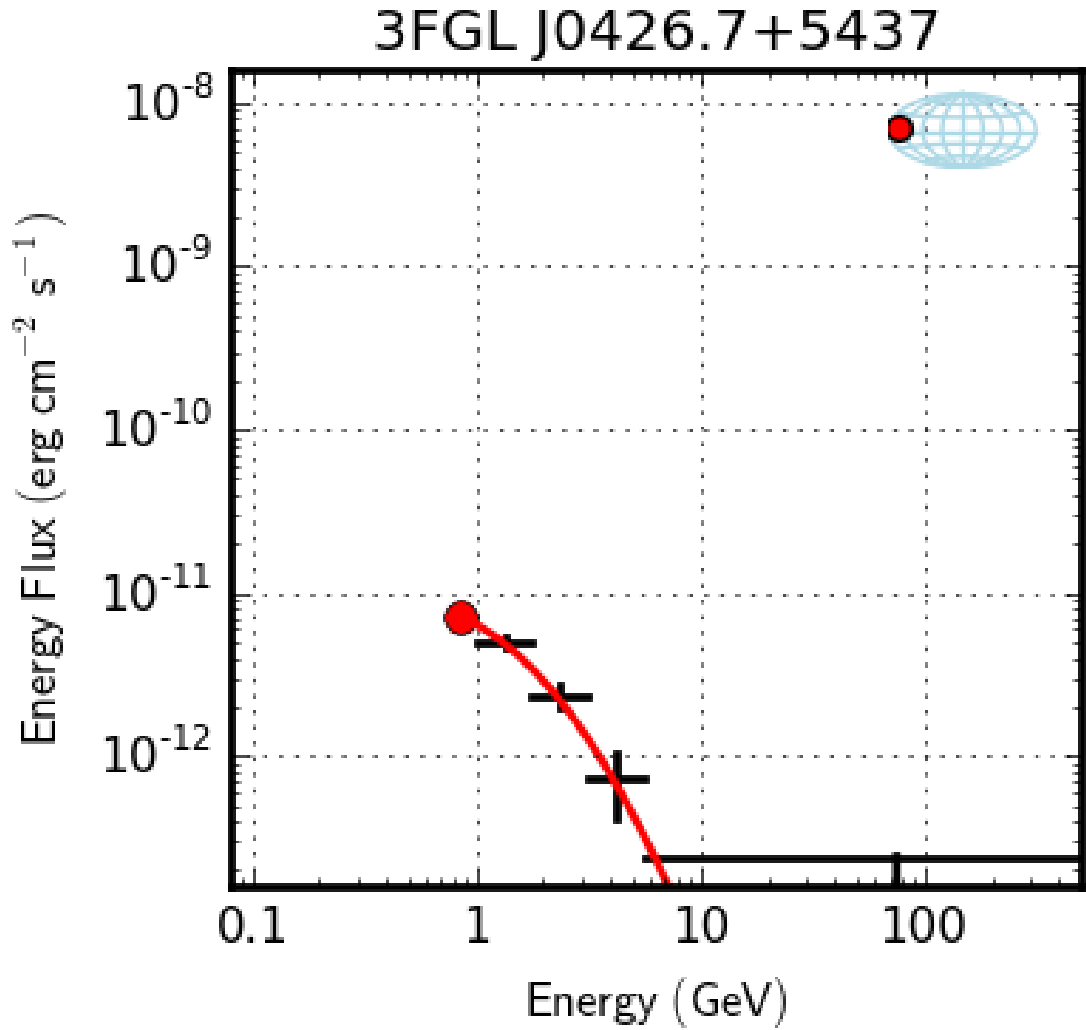
Figure 7.4: Spectral energy distribution of 3FGL J0426.. [JAM: replace with gtlike SED when I have it]

7.4 Discussion and Results

7.4.1 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 $\text{flux}_x/\text{flux}_g \propto$ 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 $\approx$ 5kyr, maybe this is a transitional SNR? What do others like this look like? Puppis A? Gamma Cygni is a similar age too.something

7.4.2 Distance Considerations

probably doesn't need to be a different section.

7.4.3 Nonthermal Modeling

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

7.5 Conclusions

[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 γ -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 γ -rays in 2FHLabove 50 GeV. We discussed our LATmorphological 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 2FHLresult. Discuss potential source origin scenarios. Is it SNR or PWN? Is 2FHLsource same as $>$ 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 γ -ray emission, relation to SNR and 2FHLsource1

Chapter 8

SNR-MC, 10 GeV, and anything else?

Not sure how this is going to factor in yet. supernova remant 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.

CGRO Compton Gamma-Ray Observatory.

CR cosmic ray.

EGRET Energetic Gamma-Ray Experiment Telescope.

FoV field of view.

GBM Gamma-ray Burst Monitor.

GRB gamma-ray burst.

IC inverse compton.

LAT Large Area Telescope.

PSF point spread function.

PWN pulsar wind nebula.

RoI region of interest.

SED spectral energy distribution.

SNR supernova remnant.

SNR-MC supernova remant molecular cloud system.

SNRcat First *Fermi*-LAT Supernova Remnant Catalog.

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