Abstract

Title of Dissertation: γ-Ray Studies of Stellar Graveyards: Observations of Extended Emission in the Galactic Plane

Jamie Michael Cohen, Doctor of Philosophy, 2016

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Here I shall abstract!

γ-Ray Studies of Stellar Graveyards: Observations of Extended Emission in the Galactic Plane

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)

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

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

-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 Energetic Gamma-Ray Experiment Telescope (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

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

Chapter 5

The 1st *Fermi*-LAT Supernova Remnant Catalog

[JAM: Change chapter title to reflect the work I've done more] [JAM: Refs from snr cat paper aren't working yet]

5.1 Introduction

One of the primary science goals of *Fermi*was to fill in the high energy gamma sky, the end of the EGRET era left us with Hartman et al. (1999)

limit of EGRET was it's large error boxes (this just means not great spatial resolution right?)

(Yadigaroglu & Romani 1997) γ-ray sources correlate with massive star forming regions (sturnder dermer also?) 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

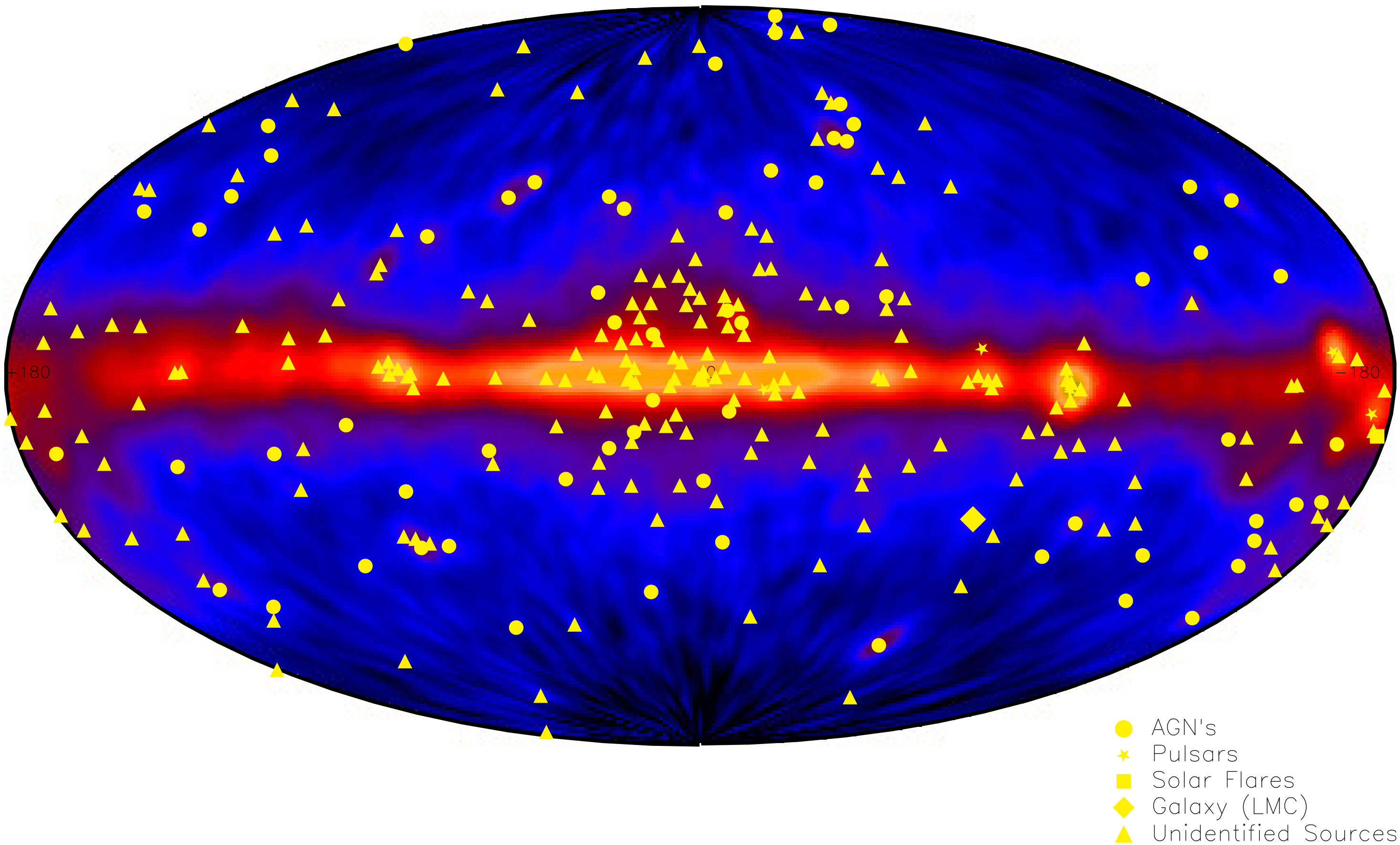

Figure 5.1: Third EGRET catalog all-sky map. Unidentified sources represented by triangles. Image courtesy of `https://heasarc.gsfc.nasa.gov/docs/cgro/images/epo/gallery/skymaps/`

2. Understand the mechanisms of particle acceleration in celestial sources:

271 sources (above 100 MeV, 170 with no firm identification, 81 within $|b| < 10°$

-what's to gain from studyng the population

-constraint on CR energy density in the Galaxy

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

EGRET statistical association with SNRs, but not concrete association what do we learn about them that's unique to γ-ray's and the LAT?

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

best fit under simplest assumptions

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

5.2 The `pointlike` Maximum Likelihood Package

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

idk if addSrcs needs to be it's own section yet

5.3 Input Source Model Construction

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].

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 $\leq 2.6^\circ$ 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 $\sim 0.7^\circ$ (Ackermann et al. 2012). 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 $0.1^\circ \times 0.1^\circ$ 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

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

fitting without the source, i.e., 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:

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

where N is the integrated photon flux, Γ is the photon index, and $E_{\rm min}$ and $E_{\rm max}$ 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 Γ and localized the newly added source. The significance of a point source with a PL spectral model is determined by the χ^2_n distribution for n additional degrees of freedom for the additional point source, which is typically slightly less than $\sqrt{\rm TS}$[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 $\rm TS_{bandfits}$. A value for $\rm TS_{bandfits}$ much greater than the TS calculated with a PL ($\rm TS_{PL}$) sug-

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

gests 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 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 GeV. If $\mathrm{TS}_{\mathrm{bandfits}} - \mathrm{TS}_{\mathrm{PL}} \geq 25$, 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: $\mathrm{TS}_{\mathrm{curve}} \equiv 2(\log \mathcal{L}_{\mathrm{logP}} - \log \mathcal{L}_{\mathrm{PL}}) \geq 16$. 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 TS < 16 for three consecutively added new sources, denoted as $\mathrm{N}_{\mathrm{TS}<16} = 3$. 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 $\mathrm{N}_{\mathrm{TS}<16} = 3$ was chosen to avoid missing sources with TS ≥ 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 $\mathrm{N}_{\mathrm{TS}<16} = 6$ and counted how many TS ≥ 25 sources would be excluded if a smaller $\mathrm{N}_{\mathrm{TS}<16}$ criterion was used. Reducing the threshold to $\mathrm{N}_{\mathrm{TS}<16} = 3$ 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 $\mathrm{N}_{\mathrm{TS}<16} = 3$ 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 $1-100\,\mathrm{GeV}$ 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 $\mathrm{TS}_{\mathrm{cut}} \equiv 2(\log \mathcal{L}_{\mathrm{PLEC1}} - \log \mathcal{L}_{\mathrm{PL}})$ and $\mathrm{TS}_b \equiv 2(\log \mathcal{L}_{\mathrm{PLEC}} - \log \mathcal{L}_{\mathrm{PLEC1}})$ to determine which to use. If $\mathrm{TS}_{\mathrm{cut}} < 9$ is reported for the pulsar in 2PC then a PL model is used. If $\mathrm{TS}_{cut} \geq 9$, we then check to see if the cutoff energy fit in 2PC lies within the restricted energy range of $1-100\,\mathrm{GeV}$

used in this work. For pulsars with cutoffs $\geq 1\,\mathrm{GeV}$, we then use the PLEC model if $\mathrm{TS_b} \geq 9$, 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.

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.

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

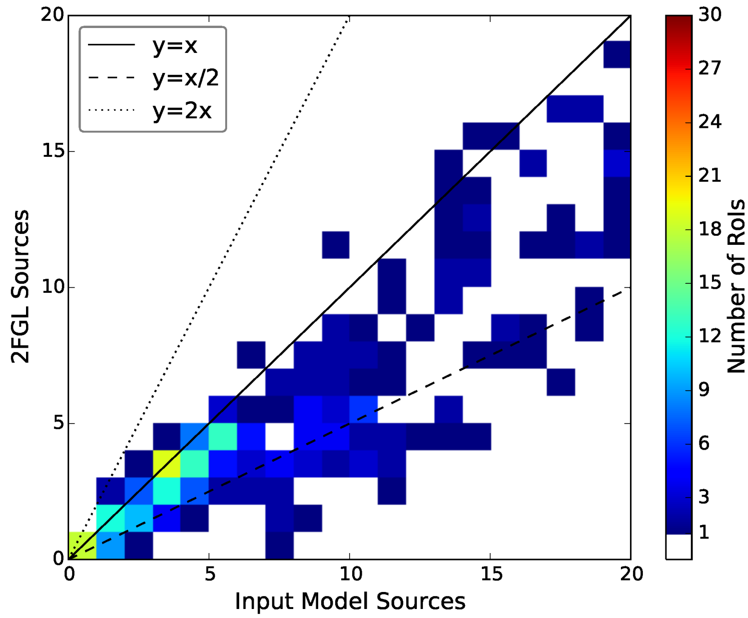

Figure 5.2: Comparison of the number of 2FGL sources with $\mathrm{TS}_{1-100\,\mathrm{GeV}} \geq 25$ (excluding AGN and pulsars) with the number of newly added input model sources in the present analysis, for sources within 3° of the center of each RoI. The color scale shows the number of RoIs with a particular combination of numbers of 2FGL sources and new sources. White corresponds to no RoI with that combination of source counts.

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.

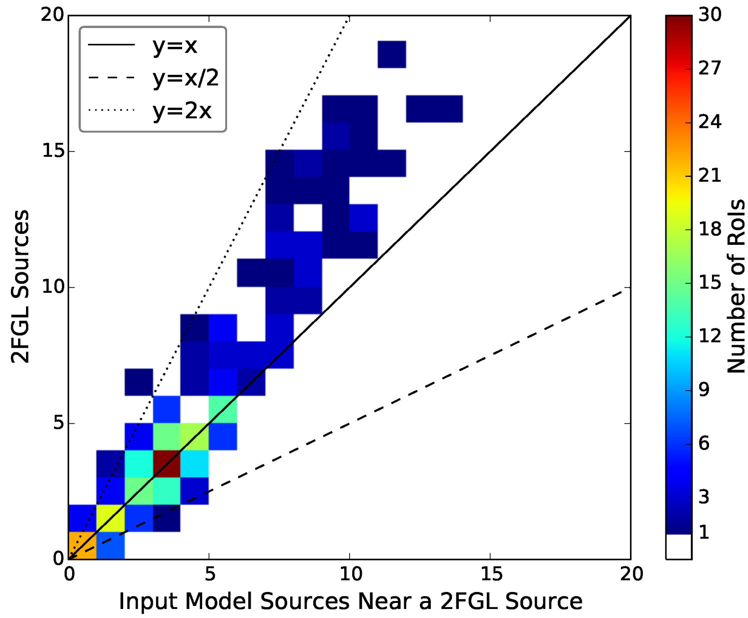

Figure 5.3: Same as Figure 5.2, including only input model sources lying within 0.2° of a 2FGL source.

5.5 Scratch

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

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 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

SNR G150.3+4.5

Dedicated analysis of one interesting Second Catalog of Hard Fermi-LAT Sources (2FHL)result. 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

6.1 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 §6.2, detail multiwavelength observations in §6.3, and discuss various emission origin scenarios in §6.4.

6.2 *Fermi* LAT Observations and Analysis

6.2.1 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

[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, TS $= 2\ \mathrm{Log}(\mathcal{L}_1/\mathcal{L}_0)$ 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.

6.2.2 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 §6.4.2).

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 6.1 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

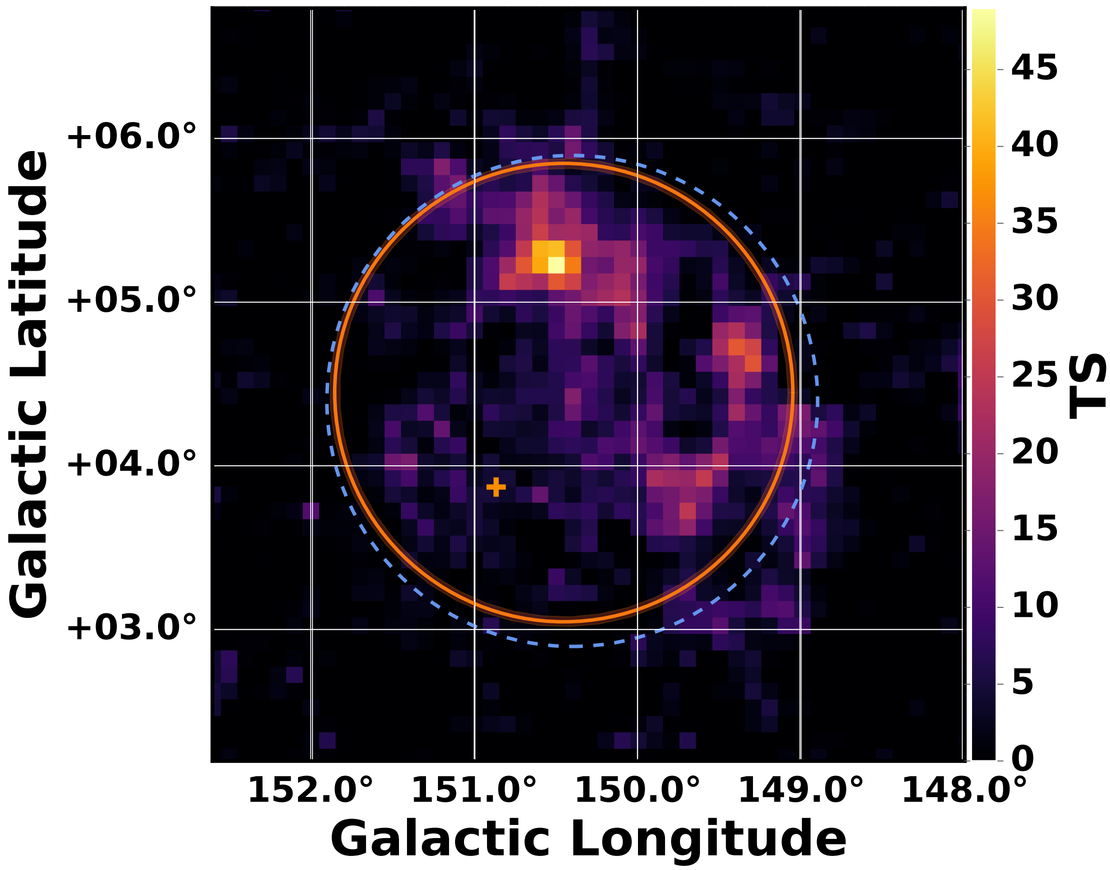

Figure 6.1: Background subtracted residual TS map above 1 GeV with 0.1°x 0.1° pixels for fixed index $\Gamma = 2$, centered on SNR SNR G150.3+4.5. The orange circle and translucent shading show the fit disk radius and 1σ errors, respectively, for the extended source, the orange cross shows the position 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 6.2 is a Residual TS map of the same region as Figure 6.1, 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

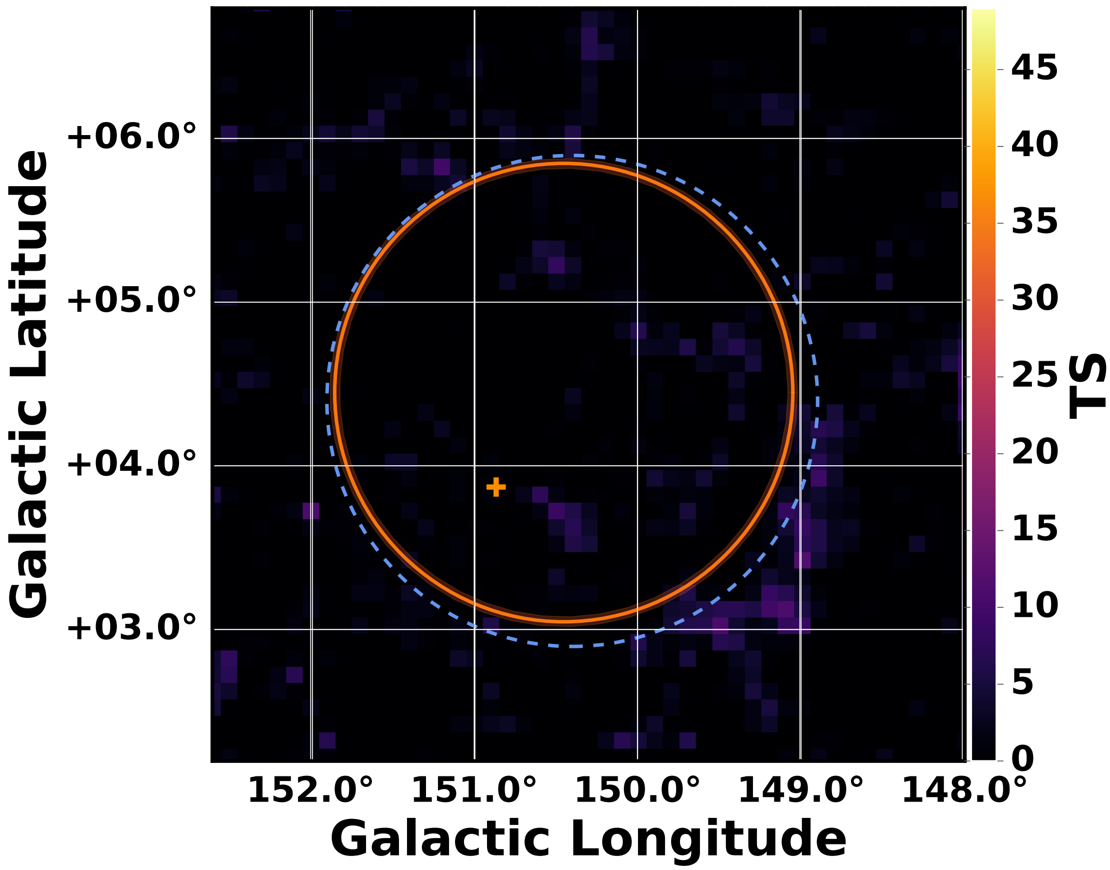

Figure 6.2: Same as Figure 6.1 but with disk in the background model [JAM: should this be a residual counts map instead?]

model at the 2.6σ level ($\Delta\mathrm{TS} = 9$ 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

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 6.2.

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.

6.2.3 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 ± 0.73 x10^{-11}) erg cm^{-2} s^{-1}and TS = 373 [JAM: these are the pointlike 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 $\sim$ 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

6.3 Multiwavelength Observations and Analysis

6.3.1 HI

6.3.2 CO?

Do the CO maps add anything?

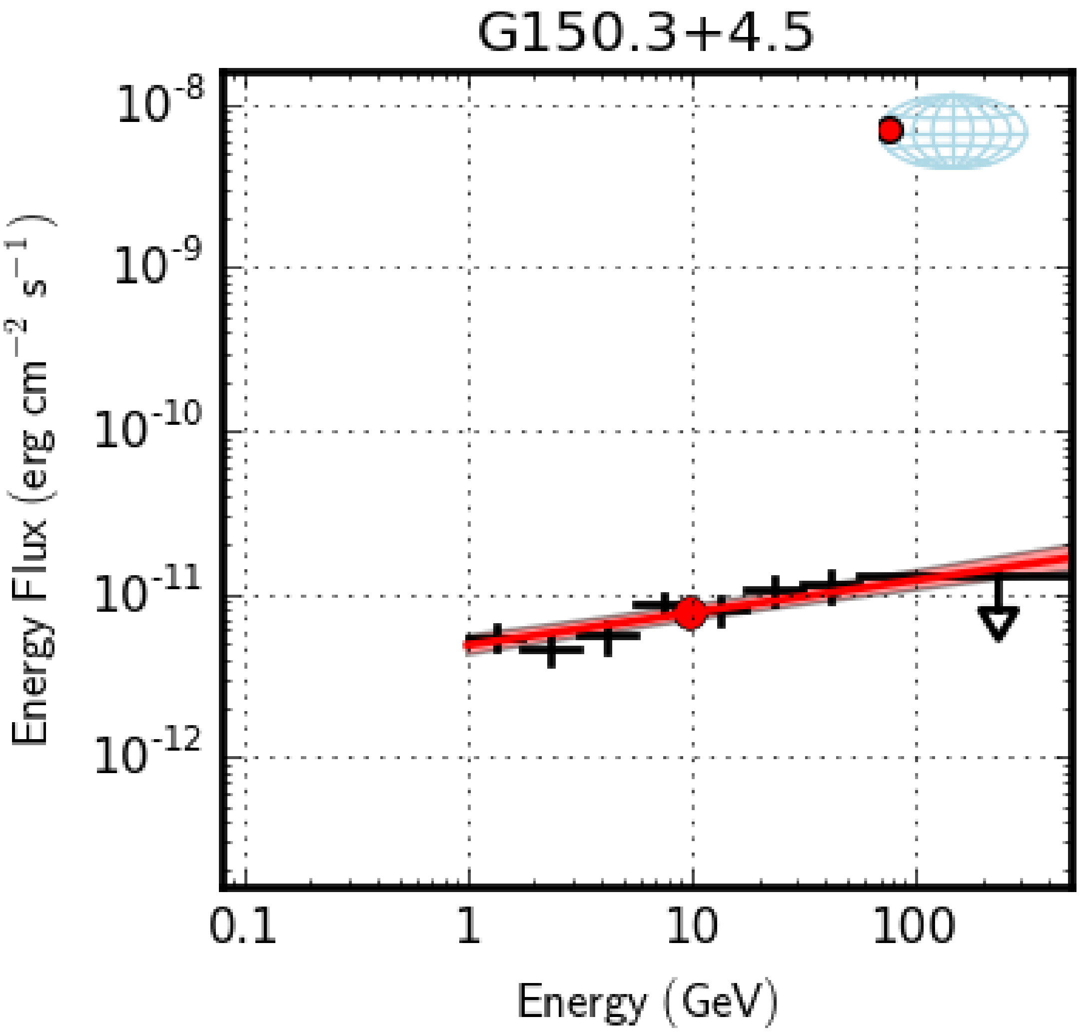

Figure 6.3: Spectral energy distribution for the extended source coincident with SNR SNR G150.3+4.5. [JAM: replace with gtlike SED when I have it]

6.3.3 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?

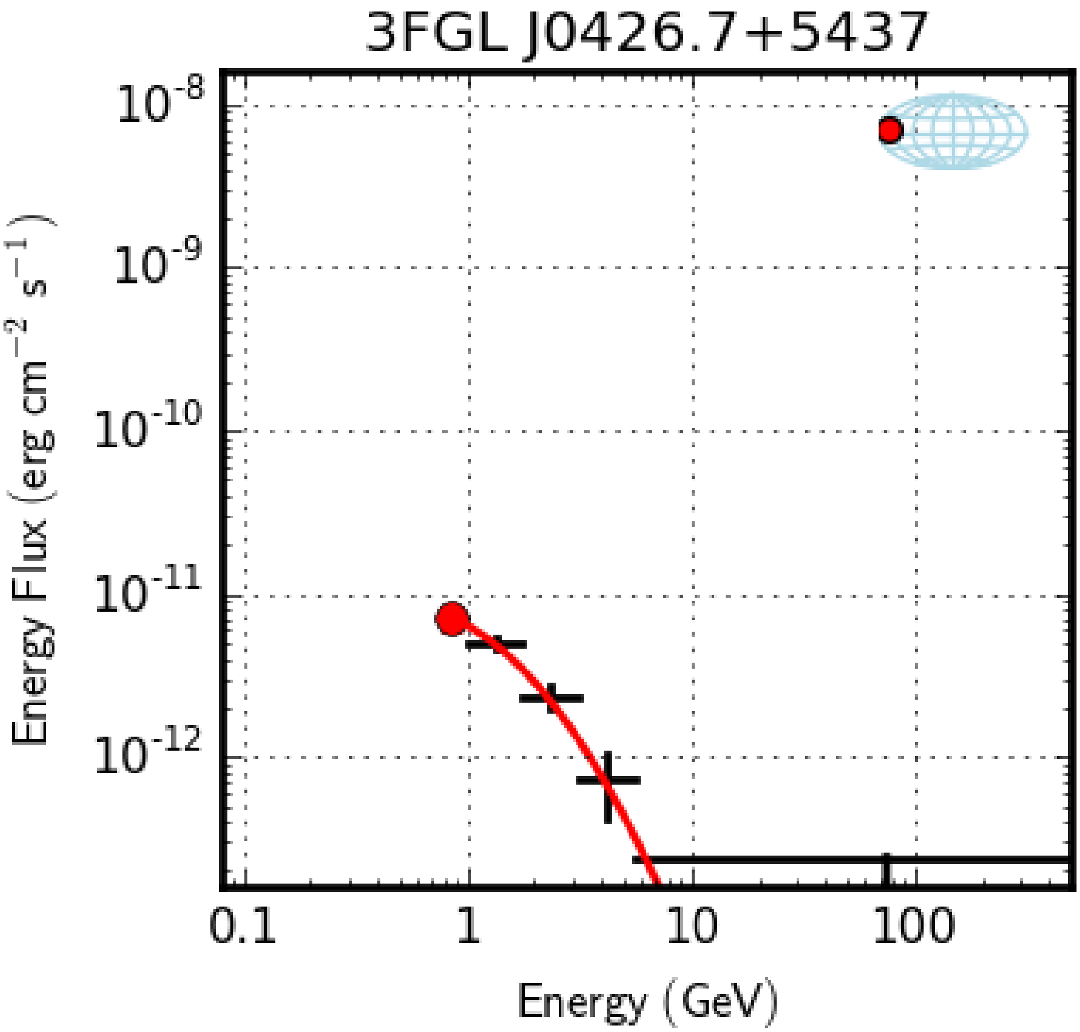

Figure 6.4: Spectral energy distribution of 3FGL J0426.. [JAM: replace with gtlike SED when I have it]

6.4 Discussion and Results

6.4.1 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 $\mathrm{flux}_{\mathrm{x}}/\mathrm{flux}_{\mathrm{g}} \propto$ 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

6.4.2 Distance Considerations

probably doesn't need to be a different section.

6.4.3 Nonthermal Modeling

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

6.5 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 7

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 8

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.

EGRET Energetic Gamma-Ray Experiment Telescope.

GBM Gamma-ray Burst Monitor.

GRB gamma-ray burst.

LAT Large Area Telescope.

PWN pulsar wind nebula.

RoI region of interest.

SNR supernova remnant.

SNR-MC supernova remant molecular cloud system.

SNRcat First Fermi-LAT supernova remnant catalog.

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