Fermi-LAT Observations of Extended Gamma-Ray Emission in the Direction of SNR G150.3+4.5

Jamie M. Cohen, Elizabeth Hays, John W. Hewitt

ABSTRACT

We report here a dedicated analysis of the γ-ray emission around supernova remnant (SNR) G150.3+4.5, observed with the Large Area Telescope (LAT) on board the *Fermi Gamma-Ray Space Telescope*. The Second Catalog of Hard *Fermi* LAT Sources reported detection of a hard spectrum, spatially extended source from 50 GeV - 2TeV, partially overlapping G150.3+4.5. Lowering the energy threshold to 1 GeV we significantly detect a large ($\sigma = 1.40° \pm 0.03°$) extended γ-ray source consistent with the entirety of the radio shell and displaying a power law spectral index of 1.88. [JAM: all these numbers need to be finalized with the gtlike analysis] An obtained HI spectrum toward the SNR suggests that the remnant could be one of the closest to us and estimates of its age indicate that G150.3+4.5 may be in the Sedov-Taylor phase [JAM: not sure about this, maybe distance is very uncertain, and hence age as well? My age estimate was $\sim$ 6kyr. Need to think about dynamically young vs. young, fast shocks like which SNR? does dynamically young say something more about the progenitor explosion or surrounding medium?]. In contrast, the spectrum of the γ-ray source is more akin to that of a young, leptonic dominated SNR, although ROSAT X-ray observations show no signs of nonthermal emission coincident typically observed in young SNRs. We discuss alternate origin scenarios for the γ-ray emission... [JAM: Should I have the words Pass 8 here somewhere, make it all shorter? move the on board stuff to intro.]

Subject headings: Supernova Remnants, γ-rays, Cosmic rays, Radio

1. Introduction

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

We describe the LAT and analysis results in §2, detail multiwavelength observations in §3, and discuss various emission origin scenarios in §4.

2. *Fermi* LAT Observations and Analysis

2.1. Data Set and Reduction

Fermi LAT is 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

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* LAT catalog (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 in 3FGL. We added to the RoI several point sources to account for this unmodeled emission and minimize the global residuals.[JAM: do I need to say more about these sources? should I mention adding them automatically and 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 likeli-

hood fit of the RoI was performed, and sources with a test statistic (TS) < 9 (TS is defined as, $TS = 2 \, \mathrm{Log}(\mathscr{L}_1/\mathscr{L}_0)$ where $\mathscr{L}_1$ is the likelihood of source plus background and $\mathscr{L}_0$ that of just the background) were removed from the model.

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. To strike a balance between the best angular resolution and minimal 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 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 G150.3+4.5further in §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 1 shows a residual TS map for the region around 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. [JAM: add something somwhere about contamination with J0426

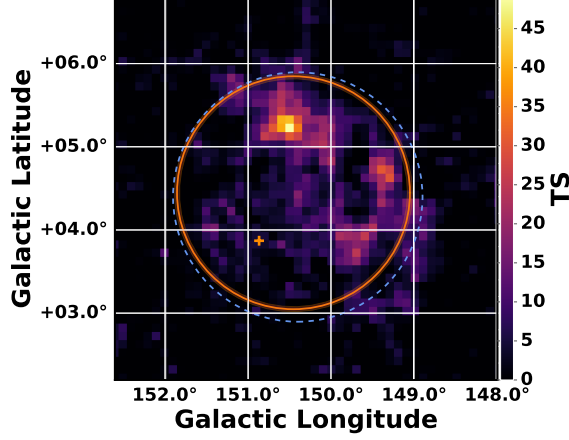
Fig. 1.— Background subtracted residual TS map above 1 GeV with 0.1°x 0.1° pixels for fixed index $\Gamma = 2$, centered on SNR G150.3+4.5. The orange circle and translucent shading show the fit disk radius and 1σ errors, respectively, for the extended source, the orange cross shows the position of 3FGL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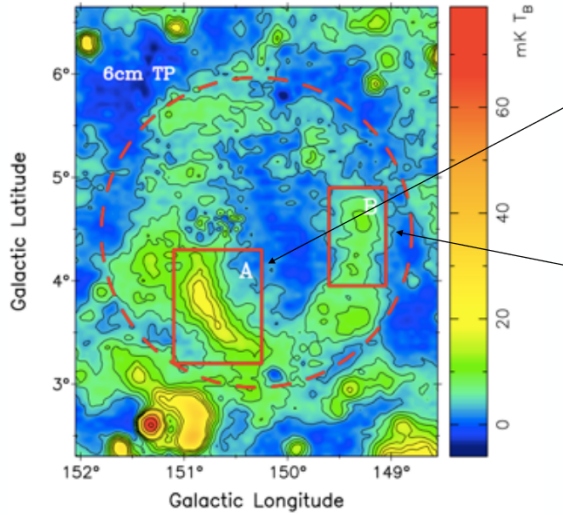

Fig. 2.— This is just a filler image for now while testing things out (Gao & Han 2014)

[133] We modeled the excess emission in the direction
[134] of G150.3+4.5 with a uniform intensity, radially-

[135] symmetric disk, simultaneously fitting the spa-
[136] tial and spectral components of the model via
[137] `pointlike`. The extension of the disk was initial-
[138] ized with a seed radius of $\sigma = 0.1°$ and position
[139] centered on the radio position of G150.3+4.5. We
[140] define the significance of extension as in Lande
[141] et al. (2012); $\mathrm{TS_{ext}} = 2\log(\mathscr{L}_{\mathrm{ext}}/\mathscr{L}_{\mathrm{ps}})$, with $\mathscr{L}_{ext}$
[142] being the likelihood of the model with the ex-
[143] tended source and $\mathscr{L}_{ps}$ that with of a point source
[144] located at the peak of emission interior to the ex-
[145] tended source. For the disk model, $\mathrm{TS_{ext}} = 298$,
[146] with a best fit radius, $\sigma = 1.40° \pm 0.03°$ [JAM: I
[147] should just put this all in a table and reference it],
[148] which is in very good agreement with the radio
[149] size of the SNR determined in Gao & Han (2014).

[150] The morphology of the radio emission is sug-
[151] gestive of an elliptical or ring morphology, so an
[152] elliptical disk and ring spatial model were tested
[153] as well. For the ring model, the fit reduced to a
[154] disk with parameters matching those stated above.
[155] Using the elliptical model showed a weak improve-
[156] ment over the radially symmetric model at the
[157] 2.6σ level ($\Delta \mathrm{TS} = 9$ with two additional degrees
[158] of freedom), which we did not consider significant
[159] enough to say the GeV emission had an ellipti-
[160] cal morphology (see Table 1). For the remainder
[161] of this study, we only considered the disk spatial
[162] model.[JAM: put Edisk in table too and reference
[163] i.]

[164] [JAM: more]

[165] Other things we tried

[166] fitting an extended source (starting with the
[167] 2FHL result) on top of the one currently there.
[168] Insignif

[169] another starting at the position of G149. In-
[170] signif

[171] Adding more point sources on top of the ex-
[172] tended source. Insignif

[173] Say something about why we don't just go with
[174] the 3 3FGL sources. In the table I shouldn't just
[175] compare the 3 to the disk though because I also
[176] keep J0426 in the model. So the base comparison
[177] is really 2 sources vs the disk. Maybe it's enough
[178] to just say of course we keep the disk, we find one
[179] at GeV that matches really well with the radio.
[180] What did Josh's paper say about how modelling
[181] the spectrum of an intrisically extended source as
[182] point sources skews the PS spectrum to softer en-
[183] ergies?

3

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.

2.3. Spectral Analysis

After determining the best fit morphology with `pointlike` for the GeV emission coincident with 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

Best fit

Describe gtlike results, spectral models tested (broken PL? no need to since it looks so power law esque?). No break observed, hard spectra increasing to TeV

how many energy bins

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

3. Multiwavelength Observations and Analysis

Not sure yet if I'll need separate sections

3.1. Radio

I don't think we're presenting any new Radio analysis, just rehashing previous results, showing radio maps overlaid on GeV, so maybe this is really discussion. (Gao & Han 2014)

3.2. HI

3.3. CO?

Make CO overlay maps for the possible velocities?

3.4. 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 something like density with an upper limit on X-ray emission? What about other x-ray telescopes?

4. Discussion and Results

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 $flux_x/flux_g \propto Edot$?

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

4.2. Distance Considerations

probably doesn't need to be a different section.

4.3. Nonthermal Modeling

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

TABLE 1

LAT ANALYSIS RESULTS

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?

5. Conclusions

REFERENCES

Abdo, A. A., et al. 2013, ApJS, 208, 17

Abramowski, A., et al. 2015, A&A, 574, A27

Acero, F., et al. 2015, ArXiv:1501.02003

Ackermann, M., et al. 2012, ApJS, 203, 4

—. 2016, ApJS, 222, 5

Atwood, W., et al. 2013a, ArXiv:1303.3514

Atwood, W. B., et al. 2009, ApJ, 697, 1071

—. 2013b, ApJ, 774, 76

Barr, E. D., et al. 2013, MNRAS, 429, 1633

Gao, X. Y., & Han, J. L. 2014, A&A, 567, A59

Kerr, M. 2010, PhD thesis, University of Washington, arXiv:1101.6072

Lande, J., et al. 2012, ApJ, 756, 5