Detecting New Sources of High-Energy Gamma Rays

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ABSTRACT

This Research Experience for Undergraduates (REU) project investigated aspects of gamma-ray astronomy, which is the study of astrophysical sources of light with energies above 1 MeV. NASA launched the Fermi Gamma-ray Space Telescope (FGST) on June 11, 2008. Using a simulated dataset and early-release data from the Large Area Telescope (LAT) on FGST, this project studied the detection of gamma-ray sources. Spectral indices and integral fluxes were obtained for both the Crab and PKS 1502+106 regions from FGST early-release data over a sixteen-day period and a two-day period respectively in late July and early August 2008. This paper found the spectral index for the Crab to be -2.16 ± 0.03, and for PKS 1502 to be -1.98 ± 0.07. The results for the Crab are compared to those from analyzing simulated data, providing evidence that there are sources in the Crab region, unresolved by the Energetic Gamma Ray Experiment Telescope (EGRET). This paper also confirms the discovery that PKS 1502 is a gamma-ray emitting blazar, and is one of the first new gamma-ray emitters discovered so far with FGST.

Keywords: Gamma rays – Crab Nebula – blazars – FGST

1. INTRODUCTION

With NASA's launch of the Fermi Gamma-ray Space Telescope (FGST; renamed from GLAST) in June 2008, high-energy astrophysicists hope to detect a variety of sources of gamma rays in the universe, including gamma-ray bursts, active galactic nuclei, and pulsating wind nebulae. Already with the Large Area Telescope instrument, FGST has made some early discoveries in both galactic and extragalactic astronomy. For example, PKS 1502+106 was identified as a gamma-ray blazar recently (Ciprini 2008). Some quasar and gamma-ray burst activity has been detected as well (Corbel and Reyes 2008; Tramacere 2008).

Its predecessor, the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory, made some initial discoveries of several hundred gamma-ray emitters. For example, EGRET clearly identified the Crab and Geminga. However, EGRET could not resolve most of what it saw. With FGST, high-energy astrophysicists hope to resolve most of the objects and classify them as AGN, pulsars, or dark accelerators.

This work focuses on gaining an understanding of the Crab nebula as a starting point. Using both simulated and first-light survey data, evidence for new sources in the region surrounding the Crab is presented, as well as evidence that some of the unresolved objects in the EGRET catalog are not strong gamma-ray emitters.

This paper will outline the steps in data analysis for both the simulated data and real data in Section 2. The results of completing the analysis will be presented in section 3. The results from the simulated data and survey data will be compared to show evidence for possible new sources in Section 4, along with the need for future observations and analysis.

2. DATA ANALYSIS

This section will cover some important basics on the Large Area Telescope (LAT) data analysis process as well as the analysis process applied to both the Service Challenge 2 (SC2) simulation data and the first-light survey data from the telescope.

2.1. LAT Analysis

The LAT has its own special analysis tools, which require FITS-formatted files as inputs. There are two types of analyses: unbinned and binned. The unbinned analysis analyzes the significance at every point within the region of interest. Binned analysis bins the region both spatially and by energy.

Regardless of the analysis method chosen, a region of the sky is selected using gtselect, with energy-range, time range, and coordinates as search parameters. Once the region of interest is chosen, an extended region must also be chosen to account for extra point sources which could affect those within the region of interest. A two-dimensional counts map and three-dimensional counts cube are produced with gtbin, to help locate potential point sources. To account for telescope pointing, a livetime cube is produced with gtltcube. The livetime cube is a record of where the telescope was pointed in the sky at a particular time, generally given by angle.

Before running the likelihood routine, a model of the region is created with ModelEditor. Known sources are extracted from the EGRET catalog, but point and diffuse sources can be added and manipulated. To model the Crab region properly, both GalProp and extragalactic diffuse sources were added to the model and were allowed to be fitted by likelihood. Galprop is a program which models the diffuse sources from within the galaxy, which are most likely unresolved point sources. The model requires using some function to describe the point sources. To make the analysis more convenient and comparable to the EGRET catalog, this work used the following power laws to fit each point source (LAT Science Tools Workbook, http://glast-ground.slac.stanford.edu/workbook/sciTools_Home.htm; LSTW):

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

where N is the integral flux, γ is the spectral index, E is the energy, E_{min} and E_{max} are the minimum and maximum energies. The minimum and maximum energies for the data presented in this paper are listed in Tables 1 and 3. The following laws were used to fit the GalProp and Extragalactic diffuse sources:

$$\frac{dN}{dE} = N_0 \quad (2)$$

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{\gamma} \quad (3)$$

where N_0 is the value for the GalProp or the prefactor for the Extragalactic and E_0 is the scale. These parameters are listed in Tables 6 and 8.

Once the model is created, for a binned analysis, source and exposure maps are created using gtsrcmaps. Source maps are simply counts maps from the input model multiplied by the exposure and convolved with a psf chosen by the user (LSWT). These are input into likelihood with gtlike, which will output the fitted counts spectra and spectral indices. Gtlike requires specifying an optimizer. For this work, two optimizers were used: DRMNFB, a down-hill simplex optimizer and MINUIT, a more sophisticated optimizer. The final step constitutes making a model map based on the output of likelihood.

2.2. SC2 Data

Service Challenge 2 is a simulated dataset used to test the LAT analysis tools. For this project, the SC2 dataset was analyzed for the Crab region, as a preliminary test before performing LAT analysis on the Survey data.

Table 1 below provides the search parameters input into gtselect. The region is centered on the Crab Nebula, with a search radius of 20 degrees and an extended radius of 30 degrees. The times listed are in Mission Elapsed Time (MET), which is counted in seconds from January 1, 2001. They are sample times and not actual dates in reality. Figure 1 shows the raw counts map produced using the CMAP option with gtbin. The point sources included in the final model are listed according to RA and DEC in Table 2 below.

2.3. Survey Data

A similar analysis was performed on sixteen days of Survey data, from late July to early August. A summary of the search parameters is given below in Table 3. The analysis was run counting photons with energies of 100 MeV instead of 30 MeV as for the SC2 dataset due to uncertainty in the response functions of the telescope. However, the range of energies permits a slight difference without losing accuracy in the results.

As with the SC2 dataset, a counts map was produced using gtbin, and is shown as Figure 2 below. The sources are again listed by RA and DEC correspondingly in Table 4. As can been seen in the Figure 2, there are only four obvious sources, including Geminga and the Crab, all of which are listed in Table 2. Unless noted, all images have RA ranges from 63.57-103.57 degrees and DEC ranges from 2.01-42.01 degrees. North points up and east points to the left. Looking at the counts map, there are clearly high photon counts in the bottom-left corner of the image.

The last part of this work involved analyzing data from August 4, 2008 and August 6, 2008 in the PKS 1502 region. Figure 3 below shows the counts map of that region within 20 degrees of PKS 1502.

3. RESULTS

Results from running the binned analysis on the simulation data in the Crab region and the survey data in both the Crab and PKS 1502 regions are presented here. Counts spectra for the Crab and Geminga are shown here.

3.1. SC2 Data

As stated above, the binned analysis was run a total of six times on the SC2 data. The sources which appeared in the final model are listed in Table 5 below with their Spectral Indices, Integral Fluxes, and TS values. The TS values are squares of the significance. The diffuse sources are listed in Table 6, with their fitted parameters. A negative or zero TS value indicates the source has no significance. The importance of this will be detailed further in Section 4.

The model map shown in Figure 4 includes every source listed and is the visual counterpart to the results of likelihood. White areas indicate the highest normalized photon count; blue areas are part of the background. Figures 5 and 6 show the counts spectra for the Crab and Geminga.

3.2. Crab and PKS 1502+106 Survey Data Results

Tables 7 and 8 provide the indexes, fluxes and TS values for the Survey data of the Crab region, with the model map and counts spectra shown in Figures 7, 8, and 9.

Based on the photon data from August 6, 2008, here are the initial estimates of the spectral index and integral flux for PKS 1502+106:

$$\text{Index} = -1.98 \pm 0.07$$
$$\text{Integral} = 6.12 \pm 0.60$$

4. DISCUSSION AND CONCLUSIONS

Clearly from Tables 5 and 7, there are sources included in the SC2 dataset which are not real. An important reason for this was to test the tools' ability to find sources which can actually be seen in a counts map. The sources listed in Table 5 are, for the most part, actually in the counts map, Figure 1. A few of the sources are transients, which would not be expected to appear in the survey data.

However, the many of the EGRET sources (which are not listed PS #) simply do not appear in the Survey counts map. There are several possible reasons for this. First, given the limited resolution of EGRET, these sources could actually be noise, diffuse gamma rays, or simply very weak emitters. Second, again due to poor resolution, they could actually be there but the RA and DEC are incorrectly measured. Third, because the LAT data is new (and may still need calibrations), the sources could be there but the LAT data needs proper calibration.

Some possible new sources are evident from Figure 2. The photon counts are high in the bottom left corner of the image. These same areas appear red in the model map, indicating that there are more sources in that region not included in the final model. Due to spatial binning and a lack of sufficient data, these possible point sources are currently unresolved.

The results could be greatly improved through a number of ways. More observations are needed to reduce the error on the spectral indices and integral fluxes for each known source in

the Crab region. With more data, new sources which were unresolved in our sample could be identified within that region and added to a model to improve upon the measured parameters. Also, due to the high variability of PKS 1502+106, more observations are necessary to confirm and improve upon the results presented in this paper.

To better understand these sources, the results of this paper should be compared with those listed in the EGRET catalog as well as other published results from ground-based gamma-ray telescopes such as VERITAS and MAGIC.

The authors thank Amanda Weinstein, Ozlem Celik, and Nick McColl for their advice and contributions during the data analysis phase of the project, and Françoise Quéval, for coordinating the REU program.

This work was completed as part of the UCLA Physics and Astronomy REU program, funded by the NSF, award number 0552500, and by the UCLA Department of Physics and Astronomy. This research has made use of the SIMBAD database and the VizieR catalogue access tool, operated at CDS, Strasbourg, France. This research has also made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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TABLE 1
Parameter Inputs for gtselect: SC2

Parameter	Value
RA (center)	83.57 deg
DEC (center)	22.01 deg
Start Time (MET)	252460800
End Time (MET)	254880000
Lower Energy	30 MeV
Upper Energy	200 GeV
Search Radius	20 degrees

TABLE 2
Source List for SC2 Data within Crab region

Model Label	Name	RA (deg)	DEC (deg)
3EG_J0423p1707	--	65.92	17.13
3EG_J0450p1105	--	72.61	11.09
3EG_J0459p3352	--	74.78	33.87
3EG_J0520p2556	--	80.14	25.75
3EG_J0530p1323	--	82.74	13.38
3EG_J0534p2200	Crab	83.57	22.01
3EG_J0542p2610	--	85.69	26.17
3EG_J0546p3948	--	86.55	39.81
3EG_J0556p0409	--	89.06	4.15
3EG_J0617p2238	--	94.3	22.63
3EG_J0628p1847	--	97.18	18.79
3EG_J0633p1751	Geminga	98.49	17.86
PS 0	--	96.4304	34.1735
PS 1	--	70.4545	25.106
PS 2	--	103.328	17.958939
PS 3	--	79.4408	32.721547
PS 4	--	91.63804583	20.92737778
PS 5	--	87.87219583	31.49598333
PS 6	--	71.95815417	39.15188333
PS 7	--	75.90379167	23.65905556
PS 8	--	69.733325	15.89540833
PS 9	--	62.90469583	22.05123056
PS 10	--	86.4519375	5.85379167
PS 11	--	97.9020125	10.18797778

TABLE 3
Parameter Inputs for gtselect: Survey

Parameter	Value
RA (center)	83.57 deg
DEC (center)	22.01 deg
Start Time (MET)	239067652.99
End Time (MET)	240470867.14
Lower Energy	100 MeV
Upper Energy	200 GeV
Search Radius	20 degrees

TABLE 4
Source List for SC2 Data within Crab region

Model Label	RA (deg)	DEC (deg)
Crab	83.57	22.01
Geminga	98.49	17.86
J0459+3352	74.78	33.87
PKS 0528+134	82.74	13.88

TABLE 5
Spectral Indices, Integral Fluxes, TS values for SC2 Data

Name	Spectral Index (error)	Integral Flux (error)	TS Value
3EG_J0423p1707	-2.99 (0.11)	7.24 (1.39)	-530.27
3EG_J0450p1105	-3.22 (0.11)	9.81 (1.73)	-480.113
3EG_J0459p3352	-2.27 (0.03)	6.19 (0.44)	1854.33
3EG_J0520p2556	-4.56 (0.83)	82.27 (62.08)	-3482.34
3EG_J0530p1323	-2.42 (0.02)	27.14 (0.91)	11186.2
3EG_J0534p2200	-2.19 (0.02)	16.18 (0.76)	8033.11
3EG_J0542p2610	-2.41 (0.02)	21.66 (1.09)	3601.8
3EG_J0546p3948	-2.97 (0.13)	6.77 (1.19)	-358.57
3EG_J0556p0409	-2.17 (0.18)	0.44 (0.25)	16.18
3EG_J0617p2238	-2.12 (0.05)	3.42 (0.48)	846.48
3EG_J0628p1847	-1.87 (0.12)	0.34 (0.16)	24.85
3EG_J0633p1751	-1.92 (0.01)	18.65 (0.41)	39763.9
PS 0	-1.68 (0.02)	1.63 (0.11)	4428.11
PS 1	-1.71 (0.06)	0.52 (0.10)	824.43
PS 2	-1.43 (0.03)	0.43 (0.04)	2494.39
PS 3	-1.43 (0.09)	0.11 (0.04)	440.17
PS 4	-2.45 (0.20)	2.83 (1.55)	-4.73
PS 5	-2.22 (0.18)	1.00 (0.57)	91.22
PS 6	-1.84 (0.02)	2.63 (0.16)	3531.87
PS 7	-2.08 (0.06)	1.61 (0.33)	459.20
PS 8	-2.40 (0.07)	3.10 (0.51)	64.40
PS 9	-2.22 (0.10)	1.04 (0.32)	-20.35
PS 10	-3.28 (0.21)	6.88 (2.21)	-392.61
PS 11	-2.32 (0.20)	0.83 (0.44)	100.70

TABLE 6
Fitted Parameters for Diffuse Sources: SC2

Name	Index / Value	Prefactor
GalProp	0.58 (0.01)	--
Extragalactic Diffuse	-2.1	1e-05 (3.72e-05)

TABLE 7
Spectral Indices, Integral Fluxes, TS values for Survey Data

Name	Spectral Index (error)	Integral Flux (error)	TS Value
Crab	-2.16 (0.03)	3.46 (0.138)	2245
Geminga	-1.97 (0.01)	7.55 (0.16)	10628
PKS 0528+134	-2.67 (0.10)	1.13 (0.13)	147
3EG J0459+3352	-1.04 (0.21)	0.004 (0.003)	11

TABLE 8
Fitted Parameters for Diffuse Sources: Survey

Name	Index / Value	Prefactor
GalProp	3.31 (0.04)	--
Extragalactic Diffuse	-2.1	28.88 (0.24)

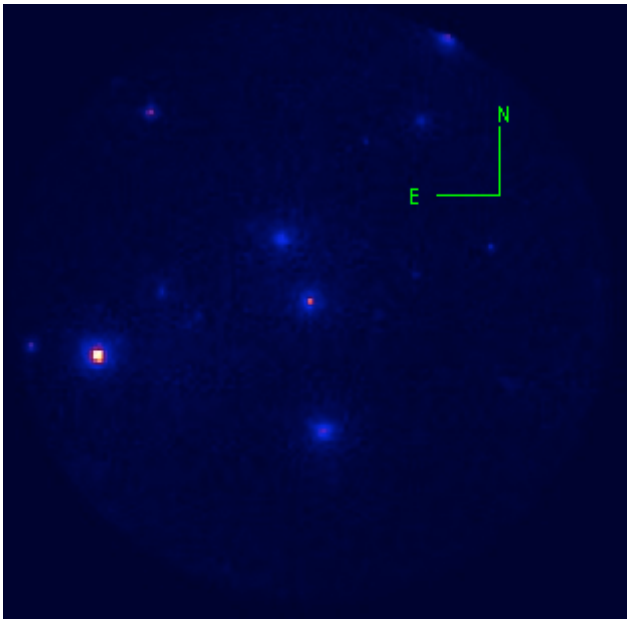

Fig. 1. – SC2 raw counts map of Crab region.
RA: 53.57-113.57 degrees. DEC: -7.99-52.01 degrees

Fig. 2. – Counts map for Survey.

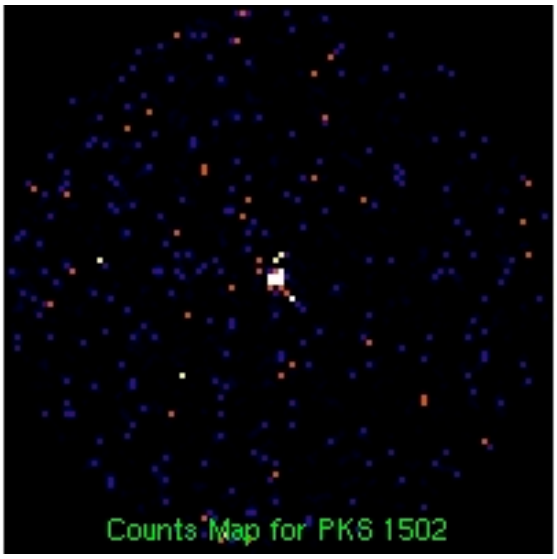

Fig. 3. – Counts Map for PKS 1502. PKS 1502 is centered in the image.

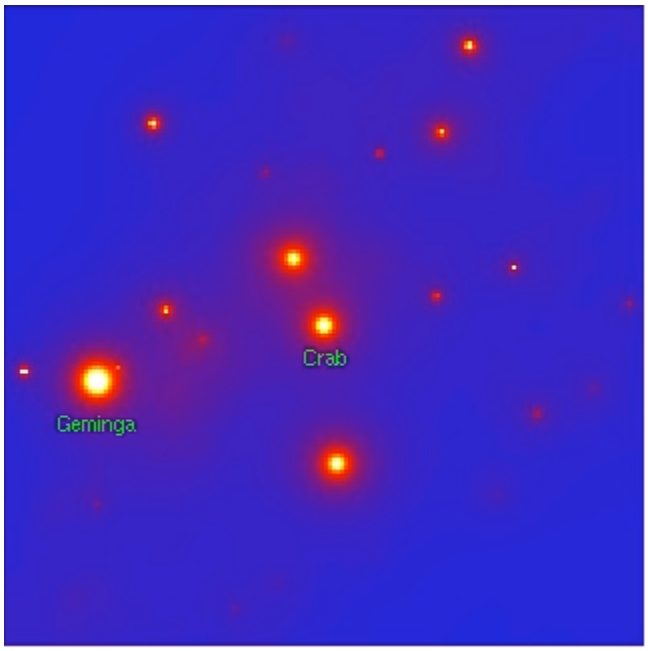

Fig. 4. – The Model Map for the SC2 Data with the Crab and Geminga labeled.

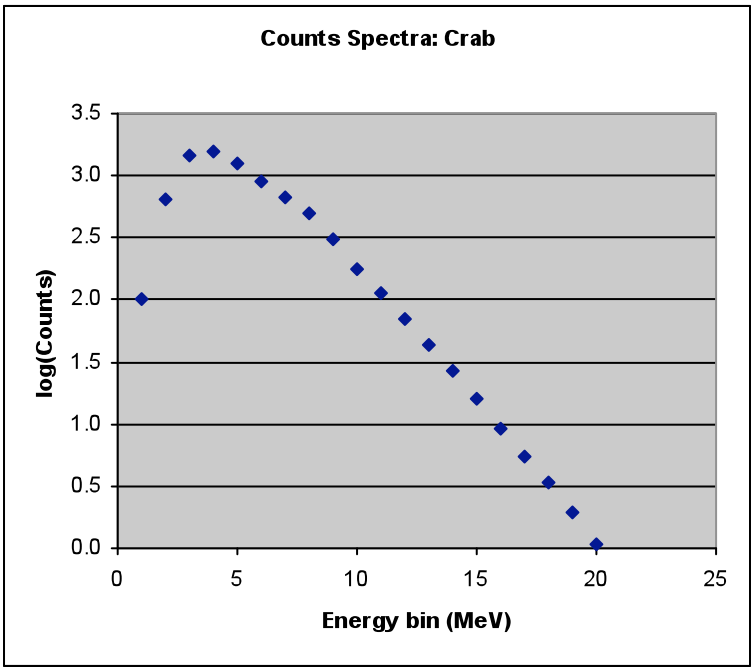

Fig. 5. – Counts Spectra for Crab. Survey.

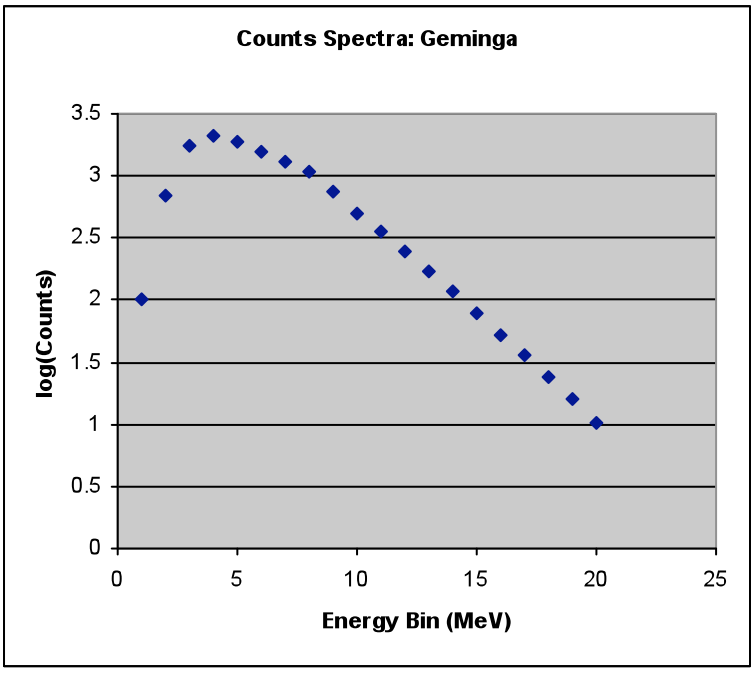

Fig. 6. – Counts Spectra for Geminga. Survey.

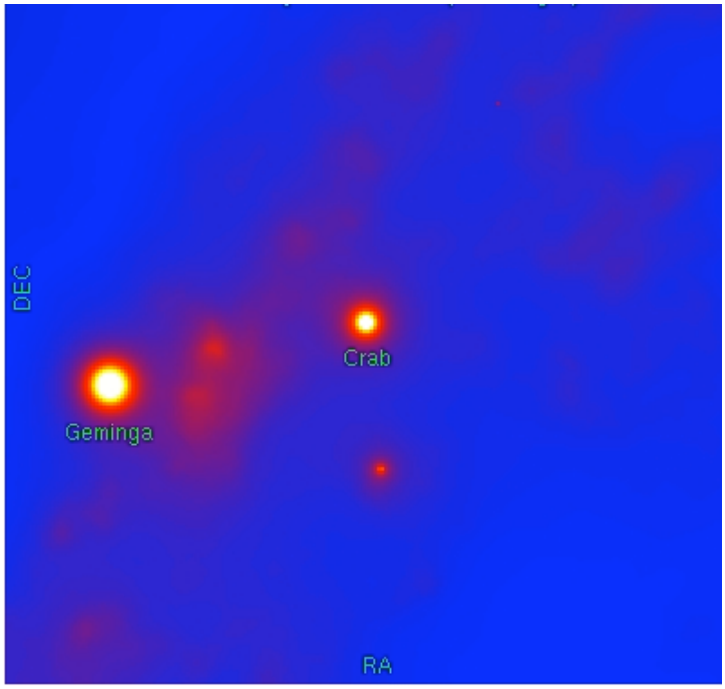

Fig. 7. Model Map for Crab region, Survey Data.
RA: 63.57-103.57 (degrees). DEC: (approximately) from 2-39 degrees.