Observations of Very High Energy Sources Using the Fermi-LAT

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Abstract

Using 5.8 years of the publicly available Fermi Large Area Telescope (LAT) data, a cluster analysis was performed, yielding 10 potential Very High Energy (VHE; E $>$ 100 GeV) sources. Each potential source was a minimum of 0.25 degrees from any known TeV source and 3 of the 10 sources were not close to any 1FGL or 2FGL source. One of the sources found was the VHE γ-ray emission from the BL Lac object RBS 0970, first noted by A. Brown [1]. An unbinned likelihood analysis is performed on each potential source, yielding 10 sources with a TS (Test Statistic) value $>$ 25.

1 Introduction

Launched on June 11, 2008, the Fermi gamma ray space telescope supports two γ-ray instruments; the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The primary instrument on this space telescope is the LAT, covering an energy range from 20 MeV to more than 300 GeV. Each photon has its arrival time, direction and energy measured. The telescope's large area allows it to see approximately 20% of the sky at any point in time, exposing all parts of the sky for 30 minutes, every two orbits ($\sim$ 3 hours). [2]

The LAT uses a technique known as pair-conversion to detect incoming photons. Gamma rays penetrate into the detector and interact with a layer of tungsten, to produce an electron-positron pair. Using silicon strip detectors, the path of the pair is tracked through the instrument. At the bottom of the LAT is a calorimeter made of CsI which is used to provide a measurment of the energy of the electron-positron pair. The energy resolution and PSF (Point Spread Function) of the LAT are shown in Figure 9 and Figure 10 of the appendix, respectively.

The most significant advantage of the Fermi-LAT is that it surveys the entire sky in an unbiased way. Ground-based telescope arrays are far more sensitive to Very High Energy (VHE; E $>$ 100 GeV) photons when compared to Fermi, however because they can only view 3.5 degrees of the sky at any time they need to know where to point beforehand. Fermi's long mission livetime allows it to create a deep exposure of the extra-galactic sky which allows us to pick out potentially interesting places for further observation. Using the publicly available Fermi-LAT data has proven successful in detecting VHE γ-ray emission from flaring Active Galactic Nuclei (AGN)[1]. This project attempts to use methods similar to those previously used by A.Brown to detect faint VHE sources. These potential sources can then be observed in more detail by the more sensitive ground-based telescopes.

1.1 Software

The Fermi data is saved as a FITS (Flexible Image Transport System) file, which is the most commonly used digital file format in astronomy. These FITS files are used as input for the various analysis tools that Fermi provides. These tools are needed in order to make the data analysis easily reproducible. The two tool packages used are *Science Tools v9r33p0* [3] and *HEAsoft v6.16* [4].

In order to make the desired cuts on the Fermi-LAT data sets, the Science Tools *gtselect* and *gtmktime* were used. *gtselect* removes photons events that are outside of a given energy range and time range. The tool can also make cuts based on the photons position in the sky and its zenith angle with respect to Fermi's reference frame. Lastly, the tool makes cuts on the the event class of a photon, which is a value representing the probability that the recorded event is a photon. The number ranges from 1 to 4, with 4 being a very high probability of being a photon.

gtmktime is used to create Good Time Intervals (GTIs) based on selections made using a spacecraft data file. A GTI is a time range when the data can be considered valid and it is used to ignore data that is collected during time periods where external factors may affect the data. Some examples of periods that are not GTIs are while the observatory is transiting the Southern Atlantic Anomaly (SAA), or during spacecraft maneuvers. The intervals are created with the help of a spacecraft file which contains the position and orien-

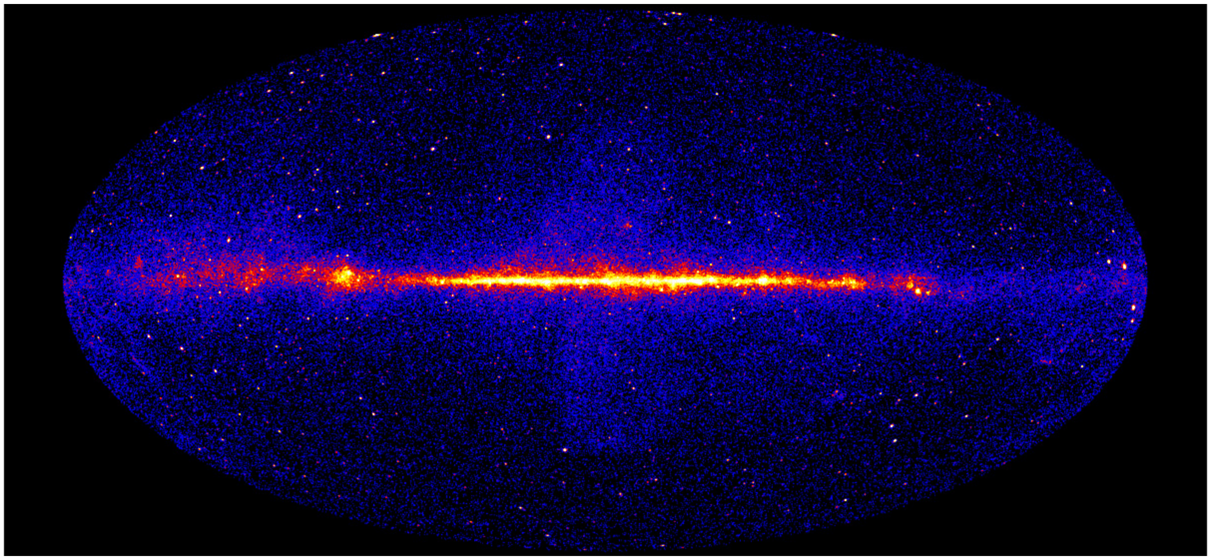


Figure 1: An Aitoff Projection of the 10 – 500 GeV energy range. The projection is given in 0.1 deg/pixel. The color scale represents the log of the number of photons in each bin. Photons are taken from the first 5.8 years of Fermi-LAT data. The color represents the number of photons, where blue is a low number and white is high number.

tation of the LAT at any time. There are three available filters for *gtmktime*: DATA_QUAL,LAT_CONFIG and ROCK_ANGLE. DATA_QUAL is a measure of quality set by the LAT instrument team (1 = ok, 2 = waiting review, 3 = good with bad parts, 0 = bad). LAT_CONFIG is the instrument's configuration (0 = not recommended for analysis, 1 = science configuration). ROCK_ANGLE is used to eliminate pointed observations, however it is not used in this project. In order to view these filtered events, the Fermi Science tool *gtbin* was used to create a counts map of the data. The photons are binned by their position in the sky and are displayed as an Aitoff projection (See Figure 1 for an example). The Aitoff projection is a commonly used map projection in astrophysics. The counts maps were viewed using the astronomical imaging application *Ds9 v7.2*[5].

At this point, several Fermi tools are used to prepare the data for a likelihood analysis, the result of which gives us the probability of obtaining observational data given an input model. The first step is to use *gtltcube* which uses the spacecraft file along with the filtered event file to compute a 'livetime cube'[1] that cover the entire sky. Once this is done, *gtexpmap* is used to create an exposure map, which is used to compute the predicted number of photons within a given Region-of-Interest (ROI) for diffuse components in a source model. *gtdiffrsp* is then used, along with a given response function, to calculate the integral over solid angle of a diffuse source model. These diffuse response values are added to the filtered event file as an additional column for each diffuse source.

At this point, we can create our source model. To create a source model based on the 2FGL catalog, Fermi provides the python script *make2FGLxml.py*. For point sources that are not associated with any 2FGL source, a source model must be created manually. We can now use *gtlike* to perform an unbinned likelihood analysis on the data. As a final check of the results *gttsmap* was used to create a 2D color map, illustrating the significance of all sources in the ROI.

The *HEAsoft* package also provides a tool kit called *ftools* which allows the user to view and manipulate FITS files. During the project, the only tools used were *fv*, which can be used to view the FITS files and *fdelrow* which deletes a specified row number from the FITS file. Lastly, many of the plots in the project as well as a large part of the analysis was done using Matlab vR2013a.

1.2 Catalogs

To get a better understanding of the LAT data, sources from four catalogs were analysed: 1FGL, 2FGL, 1FHL and TeV cat. The fist Fermi-LAT catalog (1FGL) and second Fermi-LAT catalog (2FGL), were chosen because the sources were found directly from the Fermi

[1] The livetime is the time that the LAT observed a given position on the sky at a given inclination angle. The array of these livetimes at all points on the sky is called the 'livetime cube'.

LAT data. The 1FGL catalogue is made up of 1451 sources found using the first year of Fermi-LAT data. The 2FGL catalogue is made up of 1873 sources found using the second year of Fermi-LAT data.The analysis for both catalogs is based on data in the 100 MeV to 100 GeV energy range. A power law is fit to the spectral shape for each source and its maximum likelihood is then computed [6]. A TS value (Test Statistic) is calculated for each source to categorize its significance. The threshold for inclusion is a TS > 25, which corresponds to somewhat more than 4 sigma significance. The main improvment in the 2FGL catalog is a larger observation period with improved instrument response functions and improved diffuse Galactic and isotropic models.

The 1FHL (first Fermi-LAT High energy catalog) and TeV catalog were chosen because this report focuses mainly on VHE photons. The 1FHL is made of 514 sources found by analysing data from the 10 to 100 GeV range and uses the same analysis as the 1FGL catalog. The TeV catalog is an online collection of 150 TeV sources taken from various catalogues; the list is updated by the University of Chicago.[7]

2 Data Analysis

2.1 All sky analysis

The data analysed in this paper were taken from the first 5.8 years of the Fermi LAT data. The exact time interval, given in Mission Elapse Time (MET), is 239557417 to 420991585 which equates to a calendar data of August 4 2008 to May 5 2014. An extra galactic diffuse analysis was performed on the set of photons. In Fermi's reference frame, the Earth's limb lies at a zenith angle of 113 degrees and so in order to remove any cosmic ray induced γ-rays a zenith cut of 100° was applied to the data. In order to exclude events which have a lower probability of being photons, *gtselect* was also used to cut photons with event classes less than 3. Three different energy cuts were made, using the ranges: 1 – 500 GeV, 10 – 500 GeV and 100 – 500 GeV.

From Figure 2 we can see that there is an exponential drop in the number of photons at higher energies. The number of filtered photons between the 1 – 500 GeV range is on the order of 10^6, however the number of VHE photons is only $\sim$8000. It is also interesting to note that Fermi is capable of detecting photons at energies significantly greater then the chosen cut-off energy of 500 GeV. Figure 11 in the appendix shows a histogram that was made from photons with energies $>$ 500 GeV. We can see that there are a number of photons in the TeV range, however uncertainties on these

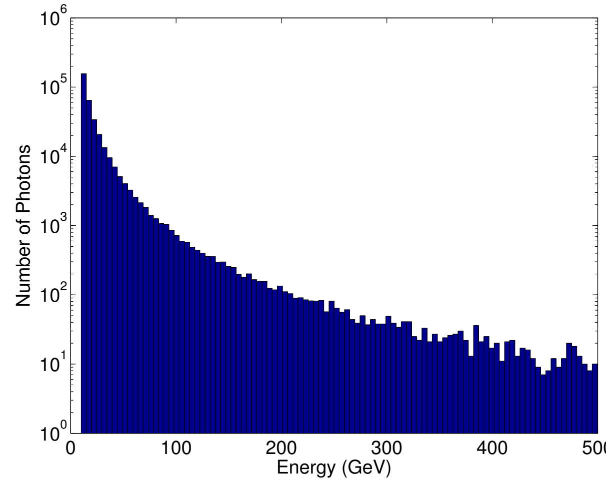


Figure 2: Histogram of the total number of photons after cuts made by *gtselect* and *gtmktime*. The energy range is 10 – 500 GeV and is divided up into 100 bins.

measurements are very large and so these events are not used.

The fermi tool, *gtmktime*, was used to create Good Time Intervals (GTIs) based on selections made using the spacecraft data file. The intervals were generated by applying a filter expression of "(DATA_QUAL>0) &&(LAT_CONFIG==1)".

At this point, the data was ready to be analysed. The first step was to see if the number of photons dropped off exponentially as a function of energy, as expected. Using the Fermi tool *fv*, we can open a FITS file and then export it as a text file. Using a program written in Matlab, the text file can then be read and separated into arrays. This made it easy to use MATLAB's hist function to create the histogram shown in Figure 2.

In order to view the effects of the cuts, *gtbin* was used to bin the data into an Aitoff projection. The projection is given in 0.1 deg/pixel, to match Fermi's PSF (See Figure 9 in Appendix). An image of the 10 – 500 GeV cut produced using ds9 is given in Figure 1.

A program was written to take as input a LAT data file and a source catalog. The program read the coordinates of the source catalog and LAT data into an array. Looping over all of the LAT data, photons within 1 degree of a source were saved with their corresponding source name. For each point source, two plots were made, the first being a weighted histogram of the number of photons as a function of angular distance away from the source center (See Figure 3 for an example).

The second plot was the energy as a function of angular distance away from the source center (See Figure 4 for an example). For large energy ranges, many sources have large numbers of photons so a 2D histogram was

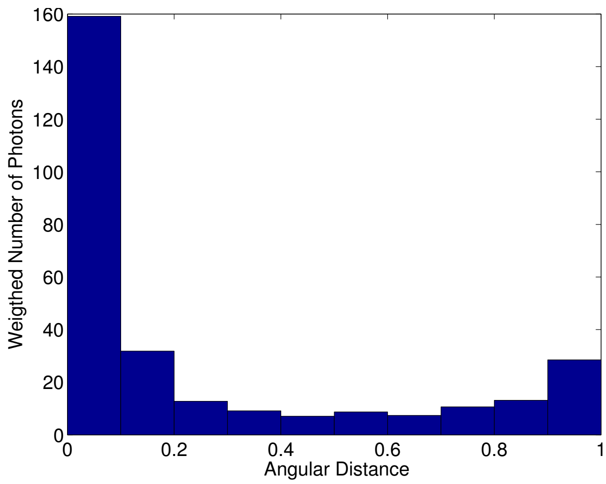


Figure 3: A histogram of the weighted number of photons as a function of angular distance from the source 2FGL J0526.1-4829. The photons in this histogram are taken from the 10 – 500 GeV cut of the Fermi-LAT. The number of photons in each bin is weighted by dividing it by the area of each bin.

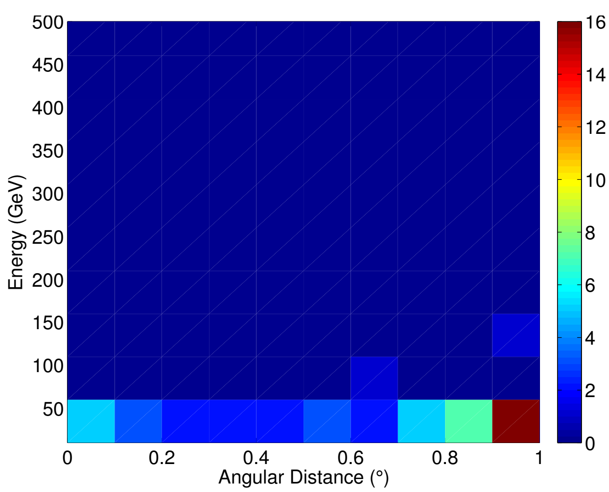


Figure 4: A 2D histogram of the energy density as a function of angular distance from the source 2FGL J0526.1-4829. The photons in this color map are taken from the 10 – 500 GeV cut. The color bar represents the number of photons inside each bin.

chosen to show where the highest number of photons resides. For sources with fewer than three photons, a scatter plot of energy vs angular distance was made instead.

A weighted histogram was chosen as a solution to the phase space problem. The position of each photon is measured as the angular distance from the source center. The photons around the source are binned by dividing the total area into concentric rings. This means that bins that are farther from the center have a much larger area and so this would show the number of photons increasing as a function of distance from the source center. To correct for this misleading result, the photon count in each ring is divided by the area of the corresponding ring. An example of a spurious result is shown in the colormap of 2FGL J0526.1-4829, in Figure 4. The largest number of photons is around 0.9°; this peak is the source 2FGL J0532.0-4826. 2FGL J0526.1-4829 is a lower energy source and so the photon count is very low with these cuts. Weighting the photons gives a much more intuitive result; even though the first peak contains very few photons, its proximity to the source center makes it much more significant (See Figure 3 for an example).We can see how this weighting also makes it easier to find clusters of photons that are significantly higher then the background.

2.2 Search for Uncatalogued VHE sources

The next step was to search for VHE sources that were not associated with any known TeV source [7]. This was done by only considering the Fermi-LAT data in the 100 – 500 GeV cut. The 500 GeV upper limit was chosen because the LAT's resolution is not defined at higher energies (See Figure 10 in appendix). A program was written to search the LAT data for any photon within 0.25 degrees from a TeV source [7]; each photon had its row number recorded. The list of photon rows was input to a bash script that used the HEAsoft tool *fdelrow* to delete these rows from the LAT FITS file. Photons within 5 degrees of the galactic plane were also removed. This was done because the high density of background photons in that region would cause a considerable number of false positives.The result was a FITS file with 3000 photons outside the galactic plane and not associated with any known TeV source.

Using these modified FITS files, a program was created to search for any photons that were within 0.2 degrees from each other. This search was motivated by analysing the Poisson statistics of the remaining number of photons. By binning the data into circles with radii of 0.2 degrees, we do not expect of see any bins containing more then 2 photons. A histogram of the

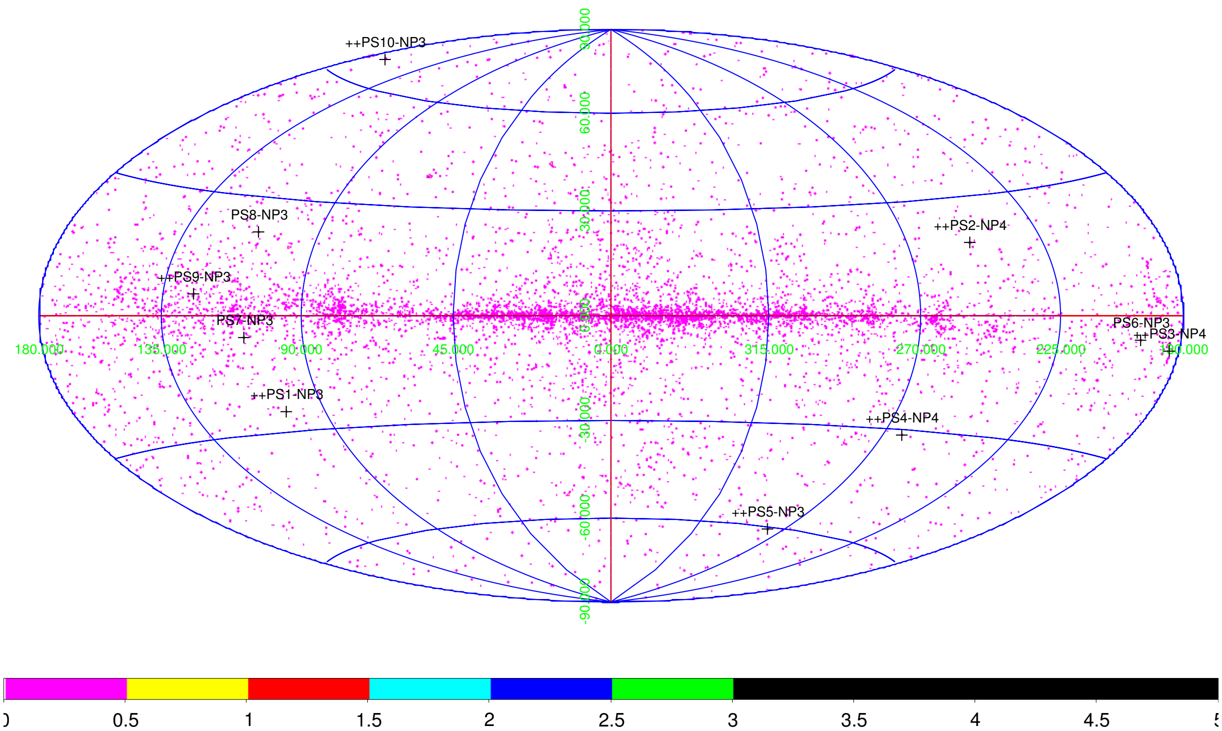


Figure 5: An Aitoff projection of all Fermi-LAT data in the 100 – 500 GeV range, after the analysis of section 2.2. The potential TeV sources are written in black. The source designation is PS x – NP y, where x is potential source, and y is the number of photons found within 0.2 degrees of each other. A '++' is added at the beginning of the source name if it is within 0.5 degrees of a 1FGL or 2FGL source.

Poisson Distribution is shown in Figure 8 of the appendix; it predicts that there should not be any bins with 3 or more photons. If a bin with 3 or more photons was found, the photon cluster was saved and the photons were removed from the FITS file to avoid double counting. For each cluster, the program would also check to see if any photons were within 0.5 degrees of a 1FGL or 2FGL source. One of the caveats of this clustering analysis is that it does not correctly identify the center of the point source. The center of the source is just the first photon that is found to have two other photons within the cut value. However, because the photons must be within 0.2 degrees of each other, this does not have a significant impact when analysing each source.

Once the the positions of the sources were determined, it was possible to download the Fermi-LAT data for a region of interest centered around the potential source [8]. The data was downloaded with a ROI of 5 degrees. Once this was done we performed a liklihood analysis as detailed in section 1.1. The filters used for *gtselect* and *gtmktime* were the same as in section 2.1, with the only difference being each source had a ROI of 5 degree. *gtexpmap* was calculated with the IRSF (Instrument Response Function) P7REP_SOURCE_V15, using 20 energy bands.

make2FGLxml.py was used for point sources within 0.1 degrees of 2FGL source to match the LAT's PSF. For other sources, a source model was made manually. The sources are fit to point source spectral models; in this project, a power law is used for each source,

$$\frac{dN}{dE} = N_0 (\frac{E}{E_0})^{\gamma} \tag{1}$$

Where N_0, E_0 and γ are the prefactor, scale and index, respectively. Point sources without any nearby 2FGL source were fit by creating a source model from 10 – 500 GeV energy cuts. This was done because the 100 – 500 GeV cuts did not contain enough photons to calculate a reliable flux. *gtlike* was then used to perform an unbinned likelihood analysis and a TS value for each point source in the source model was calculated.

By adjusting the input model file, we were able to use *gttsmap* to create two TS maps, one with and one without the potential source. This was done to see if any nearby photons were affecting the significance of the potential source.

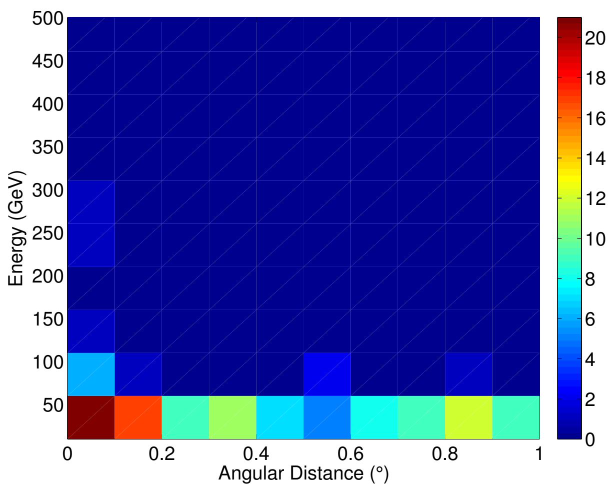
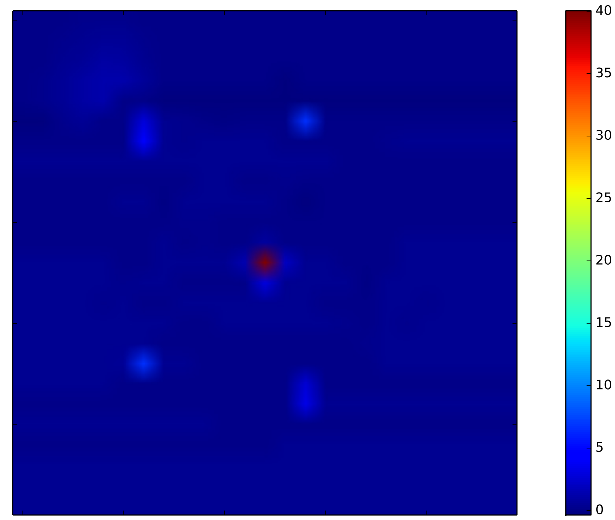
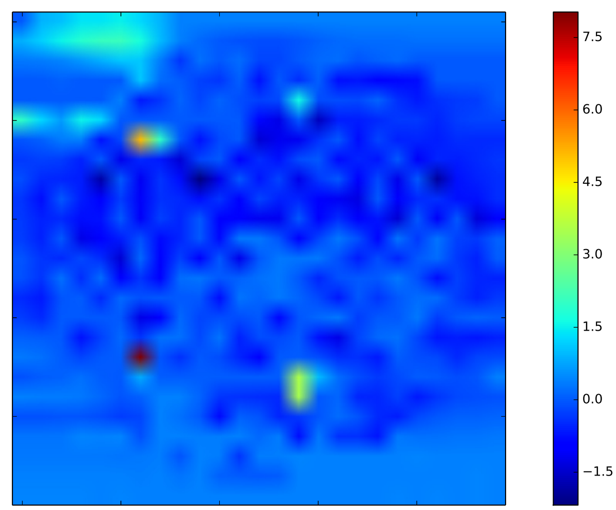


Figure 6: A 2D histogram of the energy density as a function of angular distance from the source 2FGL J0110.3+6805. The photons in this color map are taken from the 10 – 500 GeV range. We can see the three VHE photons attributed to ++PS9 – NP3



(a) With the source ++PS5 – NP3.



(b) The residual TS maps created by removing the source ++PS5 – NP3 from the source model file.

Figure 7: 2D TS maps of the potential source ++PS5 – NP3. The maps are 5 by 5 degree sections of the sky, centered around the source. A colorbar shows the significance of each color, where a TS of 25 is 5 σ.

3 Results

The sources found using the search program can be seen in Figure 5. A total of 10 clusters were found, 3 of which were not within 0.5 degrees from a 1FGL or 2FGL source. The cluster ++PS10 – NP3 is the same as the three VHE photons that Brown attributed to RBS 0970 [1]. An interesting point to note is that there are no potential sources in the center of the sky map even though this area seems to have a larger density of photons. A list of the sources found along with their TS values is shown in Table 1 in the appendix. Of the 10 sources, 5 have a TS value $>$ 35 and 5 sources have a TS value between 25 and 35. We can see that the TS value of ++PS10 – NP3 matches closely to Brown's reported value of 41.9 [1].

We can see an example of a potential source in the colormap of the source 2FGL J0110.3+6805 in Figure 6. We can see the three photons with E $>$ 100 GeV that are attributed to the source ++PS9 – NP3. The unbinned likelihood analysis for this source gave a TS value of 30.61, meaning that this source has a high statistical significance. An example of the TS maps of source ++PS5 – NP3 are shown in Figure 7. Figure 7(a) contains the potential source, and we can see that not only is the significance high, but there are no nearby sources that might be affecting the significance of ++PS5 – NP3. Figure 7(b) is with ++PS5 – NP3 removed and we can see that the significance of the residual photons are very low compared to ++PS5 – NP3.

We can see from Table 1 in the appendix that the TS value of ++PS3 – NP4 is significantly higher than any other source. A closer look at the source with ds9 shows that this is most likely caused by the extended TeV source TeV J0534+220 (Crab Nebula). An image of ++PS3 – NP4 with and without the Crab is shown in Figure 12 of the appendix.

4 Conclusion

A clustering analysis revealed 10 potential VHE sources from Fermi-LAT data. One of the potential sources was ignored as it was likely a false positive caused by it's proximity to the Crab nebula. Performing an unbinned likelihood analysis on the remaining 9 resulted in 4 sources having a TS value > 35 and 5 sources having a TS value between 25 and 35. The significance of these discoveries range from a 5σ to 7σ confidence level, meaning that these sources would be promising targets for follow-up observations with IACTs (Imaging Atmospheric Cherenkov Telescope) such as VERITAS.

An improvement for future analysis would be to use the Fermi tool *gtfinsrc* which is able to optimize a point source location using results from a likelihood analysis.

5 Acknowledgements

I thank David Staszak for his helpful discussions and his support throughout the project. I thank Kenneth Ragan for the careful proof reading of this report as well as his suggestions on improvements. I also thank the McGill VERITAS team for their helpful comments.

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A Supplemental Figures and Tables

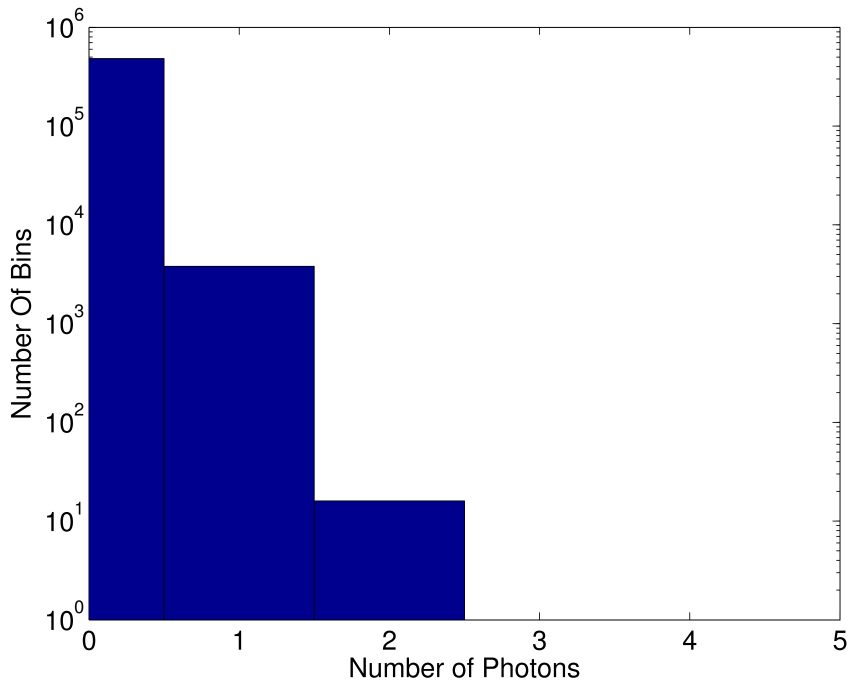


Figure 8: Poisson Distribution of photons that are filtered as described in Section 2.2. Additional cuts ensure that all photons are not within the galactic plane and are at least 0.25 degrees away from any known TeV source. The data is binned by dividing the sky into circular bins with radii of 0.2 degrees.

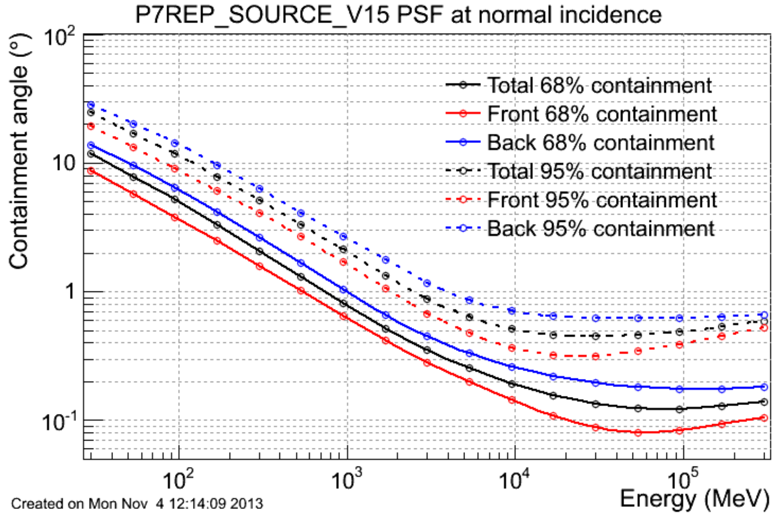


Figure 9: 68% containment angles (i.e., the radius of the circle containing 68% of the PSF) for the P7REP_SOURCE_V15 response function used in this project.

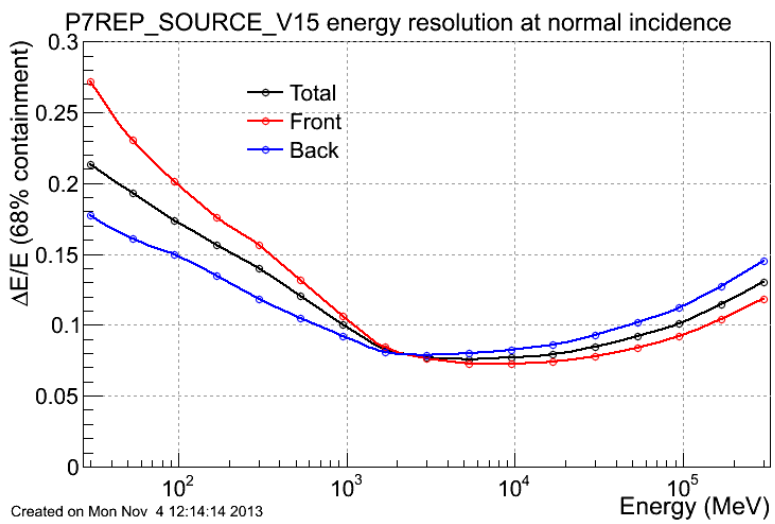


Figure 10: Energy resolution as a function of energy for normally incident photons. The energy resolution is defined using 68% containment of the reconstructed incoming photon energy.

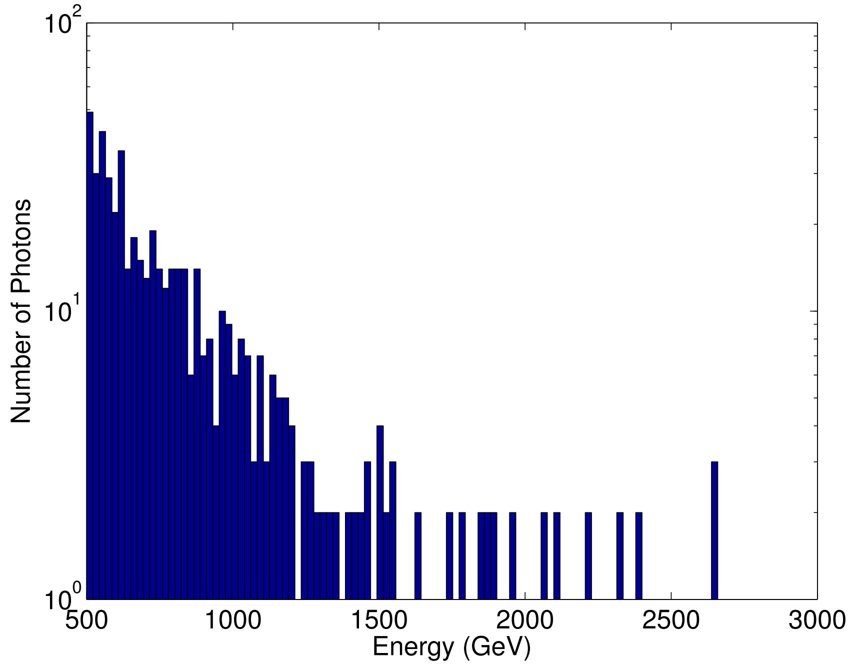
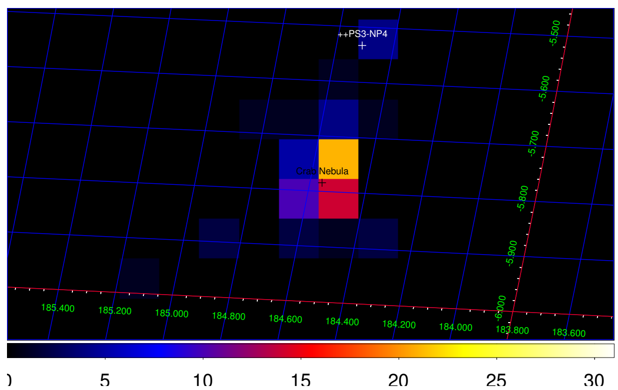


Figure 11: Histogram of the total number of photons after cuts made by *gtselect* and *gtmktime*. The energy range is 500 GeV and above, divided up into 100 bins.

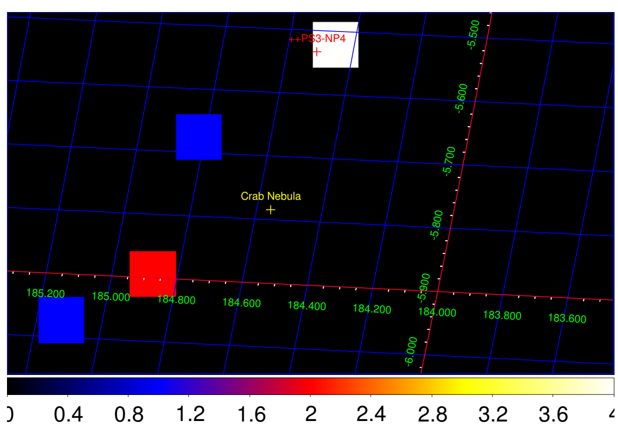
Source Name	Position (J2000)	Closest 2FGL Source	Energy of photons (GeV)	TS Value
++PS1-NP3	350.68, 34.60	2FGL J2322.6+3435	167, 105, 123	29.43
++PS2-NP4	138.30, -21.06	2FGL J0912.9-2102	138, 147, 158, 113	35.11
++PS3-NP4	83.83, 22.19	2FGL J0534.5+2201	231, 109, 102, 117	913.33
++PS4-NP4	85.97, -55.50	2FGL J0543.9-5532	167, 257, 136, 225	46.93
++PS5-NP3	32.46, -52.52	2FGL J0209.5-5229	174, 143, 127	35.12
PS6-NP3	90.07, 12.76	None	142, 101, 233	28.24
PS7-NP3	347.31, 54.43	None	112, 319, 287	30.48
PS8-NP3	306.38, 76.78	None	196, 155, 119	31.31
++PS9-NP3	17.55, 68.10	2FGL J0110.3+6805	222, 302, 132	30.61
++PS10-NP3	170.12, 42.26	2FGL J1121.0+4211	114, 117, 273[†]	41.05

Table 1: List of potential sources found, along with corresponding data.The source designation is PS x – NP y, where x is potential source, and y is the number of photons found within 0.2 degrees of each other. A '++' is added at the beginning of the source name if it is within 0.5 degrees of a 1FGL or 2FGL source.

[†]This photon was also triggered by VERITAS.



(a) With the Crab nebula.



(b) With 0.25 degrees around the Crab center removed (as outlined by the clustering analysis).

Figure 12: Image of the 100 – 500 GeV filtered event file, produced using ds9.