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Sky Watching in Gamma Rays: Searching the Universe for High Energy Processes

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Abstract. High energy events in our universe may generate photons of high energy called gamma-rays that can propagate through the universe and can be detected on Earth. Upon detection, these gamma-rays provide complementary information about high energy environments in our universe. The goal of this project is to search for these events and analyze them, using public data made available by the NASA *Fermi* Large Area Telescope mission (*Fermi*-LAT).

Keywords: Fermi-LAT, Gamma-Rays, Data Analysis, Python

1 Introduction

To start our study let's first introduce simple concepts and build upon them.

1.1 Photon

A photon is an elementary particle that is a quantum of the electromagnetic field, including electromagnetic radiation such as light and radio waves, and the force carrier for the electromagnetic force. The modern photon concept is that light itself is made of discrete units of energy. "Photon" is the popularized term for these energy units.

1.2 Gamma-Ray

A gamma-ray is a form of electromagnetic radiation arising from the radioactive decay of atomic nuclei. It consists of the shortest wavelength electromagnetic waves. Having high frequency, this radiation is made up by the photons with the highest energies, covering all the domain above 100 keV.

Gamma-rays can be originated from artificial or natural sources. Artificial sources of gamma-rays include fission, such as that occurring in nuclear reactors, and high energy physics experiments, such as neutral pion decay and nuclear fusion. Natural sources of gamma-rays can be found on Earth, which are mostly a result of radioactive decay and a secondary radiation from atmospheric interactions with comic-ray particles, or in space, from high energy events such as Gamma-Ray Bursts or flares from blazars [1, 2].

1.3 Gamma-Ray Astrophysics

As said before, gamma-rays coming from space are originated by high energy sources and the detected photons tend to vary between MeV and beyond TeV.

1.4 Gamma-Ray Detection

There are a few ways of detecting gamma-rays that are split between direct and indirect forms.

The direct forms are Compton scattering and pair production. Compton scattering is the scattering of a high frequency photon after an interaction with a charged particle, usually an electron. If it results in a decrease in energy (increase in wavelength) of the photon (which may be an X-ray or gamma-ray photon), it is called the Compton effect [3]. Part of the energy of the photon is transferred to the recoiling electron. This method is used to detect gamma-rays with 1.22 MeV or below.

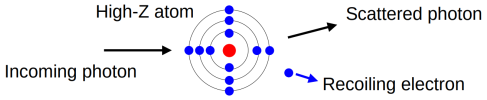

Figure 1. Compton Scattering.

Pair production is the creation of a subatomic particle and its antiparticle from a neutral boson which often refers specifically to a photon creating an electron–positron pair near a nucleus. Since the photon needs to carry more energy than the mass equivalent of the resulting particle pair, this method can only be used high-energy photons such as hard gamma-rays, with $E_\gamma \geq 1.22\,\mathrm{MeV}$.

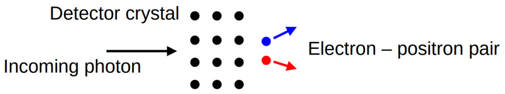

Figure 2. Pair Production.

The indirect way is through atmospheric particle showers, which are not covered in this study, so we won't go into detail, but it is important to note that when gamma rays reach Earth, they interact with the atmosphere leading to these particle showers.

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1.5 Fermi Satellite

In the last subsection, it was mentioned that gamma rays interact with the atmosphere, losing part of the information. Indeed, only the ones with energy above $E_\gamma > 30\,\mathrm{GeV}$ are powerful enough to produce air showers that can be observed from the ground. Lower energy gamma rays from astrophysical sources need to be studied out of the atmosphere. Thus, it is necessary to come up with a "method" that makes use of direct gamma ray measurements. The *Fermi* Gamma-ray Space Telescope, formerly GLAST, is used for this, which, as the name implies, is a space telescope designed to explore events in this energy range.

The *Fermi* satellite carries two instruments to detect gamma-rays:

- The Large Area Telescope (LAT, [4]): sensitive to 30 MeV $<$ E $<$ 1 TeV (nominal), with a field of view half-opening angle of approx. 60° and angular resolution of the order of 0.1°, made up by the Anti-Coincidence Detector (ACD), tracker and calorimeter.
- The Gamma-Ray Burst Monitor (GBM, [5]): sensitive to 8 keV $<$ E $<$ 40 MeV, looking all around the spacecraft, with angular resolution down to a few degrees, based on two types of sensors.

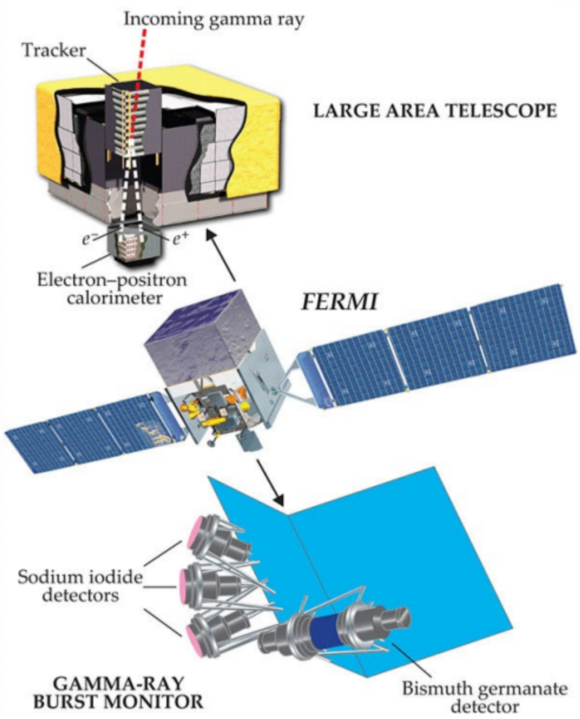

Figure 3. Fermi Satellite

Upon detection, the *Fermi* satellite can deduce the direction of origin relative to the spacecraft and its energy. In this way, by knowing the position and orientation of the spacecraft for any given event, we are able to infer the number of photons, their energy, location and detection time, forming a set of information that we represent our data.

1.6 Objectives

With the data mentioned above, we want to create the *maximum likelihood model*, which is a model that lets us reconstruct the *Fermi* observations and identify the origins of the gamma-ray sources through data analysis.

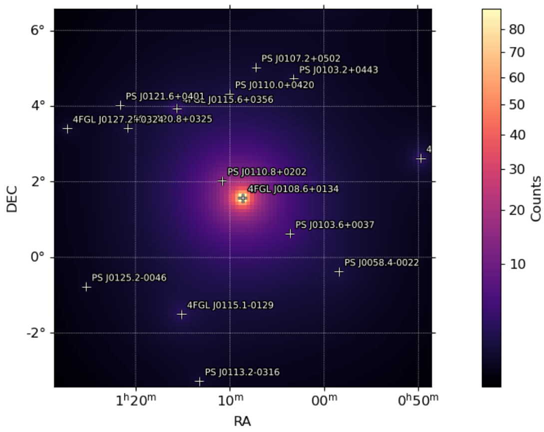

Figure 4. Example of maximum likelihood model.

The *Fermi*-LAT mission already performs analysis for a set of regularly monitored sources. We are going to work on a script that allows us to perform the same analysis, but in more general conditions, and we will compare the results.

2 Data Analysis

The analysis carried out in our procedural script follows a similar approach to the one adopted by the *Fermi* team. For this reason, we will first define the analysis process and the mathematics involved and then we will identify the differences between the analysis of the script under study and the Fermi mission.

2.1 Analysis Process

To start the analysis, we define a point in a sky map, centered on our source of interest, then we establish a circle area around that point and check the data, i.e., photons detected within that circle. This step serves to define the space we want to study.

Afterwards, we count the photons, check where they came from and we compute the probability that they were correctly reconstructed. The probability is defined by a *likelihood* function, that is, the likelihood that the photons were accurately reconstructed in terms of energy and direction. The likelihood comes in two forms:

- Unbinned Likelihood: $L = e^{-N_{\mathrm{pred}}} \prod m_i$,

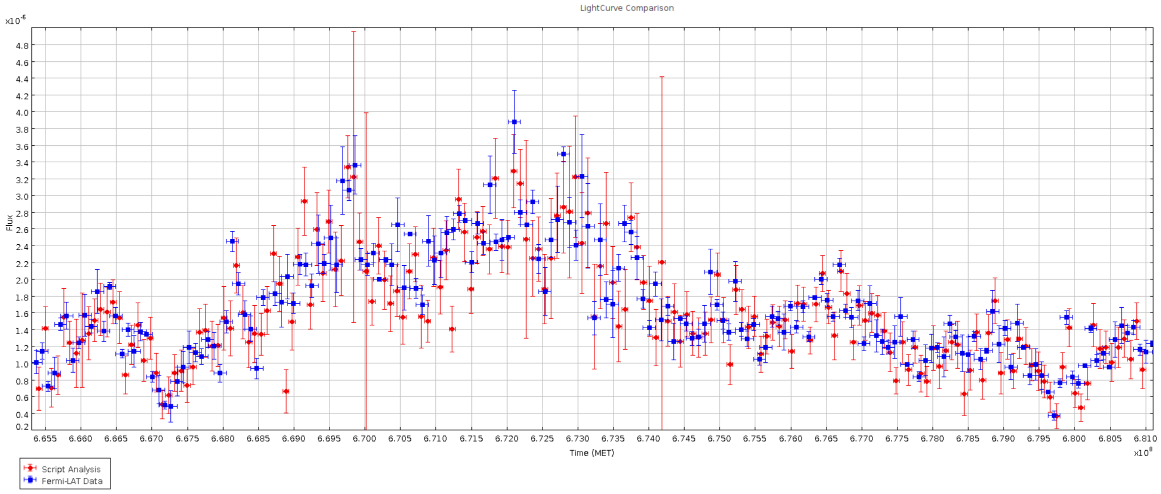

Figure 5. Daily light curve from Flare 4C +01.02 from February to July 2022. The blue points are the public *Fermi* team results, while the red ones represent the results obtained by our script.

where m_i represents the reconstruction probability of the i^{th} and N_{pred} is the total number of photons predicted by the model, or

- Binned Likelihood: $L = e^{-N_{\text{pred}}} \prod \frac{m_i^{n_i}}{n_i!}$,

where, instead, the photons are grouped in discrete bins and n_i represents the number of photons expected in every bin.

Let's talk about the unbinned approach first. In this one, we take every single photon and we apply all the reconstruction calculation to estimate its likelihood in the adopted model. Although this is the most accurate approach, this option implies a prohibitive computational effort in all cases with large number of photons (more than few hundreds). For this reason, we use the binned form. In this, the photon are grouped together according to their energy, direction and time. It is less accurate, but it is numerically more affordable and fairly reliable for studies that involve large numbers of detected photons.

To estimate the quality of our fit, we use a *test statistics*, defined as two times the logarithmic ratio between the likelihood of a model with our target of interest, with respect to the likelihood of a model with no point-like sources, i.e.:

$$TS = 2 \ln \frac{L_{\text{Target}}}{L_{\text{No target}}} \qquad (1)$$

Once the likelihood has been maximized, adding sources that are detected with $TS > 25$ (approximately corresponding to a detection threshold of 5σ), we can create our *best likelihood* model.

Finally, with the model defined, we can test which sources were detected, by localizing the brightest areas, that is, the areas where we detect the most gamma-ray photons coming from.

2.2 Analysis Comparison

The script intends to do a deeper analysis than *Fermi*'s for that, by establishing a circle on the sky map, a circle larger than *Fermi*'s is defined. On the other hand, while *Fermi*'s is limited to a grid of sources that they find interesting, our approach is in principle applicable to all the available sources. Also, when we estimate our *maximum likelihood model*, we don't focus on a single source (which is what *Fermi* does), rather we make model all the sources included in our region. The script uses data provided by the *Fermi*-LAT data center[1] and it makes use of the `fermipy`[2] *python* tool-set to run the analysis.

3 Results

Our next step is to verify the viability of our script. To do this, we run our script and compare the resulting data with the data from *Fermi*. To this end, we chose Flare 4C +01.02 as our test object, because it's a very bright flare from a source dominating the region, which implies that when we have to do the analysis it will be easy to identify the source.

The script was run from February to July 2022, to get enough data to make the comparison. The first result obtained was the energy values for each day. In fig.5 the results obtained can be verified together with the *Fermi* data.

As the figure demonstrates, the results between the script and the *Fermi* mission are similar, though some differences can be appreciated, due to slightly different time binning and to the consequences of changing the analysis approach. This result supports that, in the first instance, the script does the analysis correctly. However, some problems were identified in the following steps.

After trying to run to other options, problems started to appear with the server connection in collecting the Data for analysis, making it impossible to obtain more data. This problem is likely due to a server security policy that

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[1] `https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi`

[2] `https://fermipy.readthedocs.io/en/latest/`

does not accept duplicate requests from scripted analysis tools, resulting in an error when the requested data set is removed from the server's download storage. To solve this issue, the data set requested by the script needs to be generated and downloaded manually through the server web interface. A second problem was also identified: when trying to produce maps of "the most likely model", the program crashed and did not allow progress.

Due to the short time it was not possible to identify the flaws and solve them directly in the script. However, taking advantage from the script capability to write hard copies of the subsequent analysis steps, all the relevant plots could be extracted manually, after proper inspection of the results.

4 Conclusion

Our main objective was to compare the script analysis with that produced by the *Fermi* mission. It was possible to verify that in the first instance, we obtained a positive result in which we were able to measure the light curve of a blazar flare and have results similar to *Fermi*'s in which the difference was due to the way in which the analysis is carried out.

However, the script had some flaws - it had problems connecting to the server to collect the data for a repetition of the analysis and it crashed when we tried to compute the *maximum likelihood* model with its diagnostic plots, forcing the execution of manual analysis operations to obtain this additional output.

5 Acknowledgements

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