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Gamma-ray astrophysics with current and future detectors

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Abstract. The study investigates the Very High Energy properties of astrophysical sources, as seen by the Fermi-LAT instrument, in the context of determining the desirable performance of new ground-based observatories. In particular, focus is made on an Active Galactic Nucleus (AGN) and a Gamma-ray Burst (GRB), using data collected by *Fermi*, a spacecraft orbiting the Earth. A suite of tools specifically built to analyse *Fermi*'s data (Fermitools) allows the creation of photon count maps, light curves and spectral energy distributions, which lead to the discussion of *Fermi*'s ability to detect sources, important events as a flare and its limitations in detecting higher energies.

Keywords: Gamma-ray, *Fermi*, High energy photons

1 Introduction

1.1 Gamma-ray Sources

Gamma-ray is the most energetic radiation in the Universe, ranging from 0.3 MeV (in the Low Energy gamma-ray region) to the highest energies of the electromagnetic spectrum [1]. Although these rays can be naturally produced by radioactive decay, nuclear explosions, solar ejections or the lightning in thunderstorms, the highest energies are reached in extreme environments of the cosmos, with values that accelerators on Earth are unable to reproduce. The extremely energetic photons' sources include Supernova remnants (SNRs), interacting binaries, pulsars, gamma-ray bursts (GRBs) and active galactic nuclei (AGN), with the last two being so powerful to be detectable at extra-galactic scales.

SNRs are the product of massive star explosions and have a specially great impact on their host galaxies' chemical enrichment and evolution. SNR shocks interact with the surrounding medium, heating and compressing it, as well as accelerating particles to relativistic energies.

Binary systems where a compact component interacts with its companion can also produce gamma-rays. They are believed to be produced by particles accelerated either within a relativistic jet, or by a pulsar wind colliding with the stellar wind and/or the outflowing equatorial disk of the massive star.

Pulsars are rotating neutron stars which are continually spinning down due to electromagnetic dipole torques, losing most of their energy to magnetized particle winds and a smaller part to radiation, mostly gamma-rays.

AGN are galaxies whose center is powered by the accretion onto a supermassive black hole, which accelerates relativistic jets of ejected material to speeds near the speed of light. GRBs are the most energetic explosions in the Universe, thought to be created by the death of massive stars and merging binary neutron stars [2]. While AGN can be persistent sources of gamma-rays, GRBs are characterized by short bursts of radiation, as the source gets disrupted in the process.

1.2 Fermi Gamma-ray Space Telescope

The Fermi Gamma-Ray Space Telescope (*Fermi*) is a spacecraft that orbits the Earth since June 11, 2008, with the main purpose of collecting data from the most energetic radiation sources that could not be observed by previous monitoring instruments operating within the Earth's atmosphere, as well as continuing the study of the already known phenomena. With a few more than 10 years of collected data, *Fermi* has extracted information of gamma-ray photons ranging from 30 MeV to 500 GeV, energy orders up to 10^{12} times greater than our eyes sense [1]. These measurements can give scientists new insights about the origin of cosmic rays, the first stages of the Universe, the nature of Dark Matter or the behaviour of Black Holes. *Fermi* spacecraft carries two instruments:

Large Area Telescope (LAT)

This is the principal instrument of *Fermi*, catching photons in the range 30 MeV - 500 GeV. It has a very large field of view that allows a full-sky coverage in 3 hours. It rejects the cosmic charged particles, selecting only the photons (about 0.03 % of all the incoming particles). This is achieved by a system made of a Tracker, where photons are converted to positron and electron pairs, through conversion foils, an Anticoincidence Detector (if the incoming particle is a photon, it does not interact with the detector; if it is a cosmic ray charged particle, the detector is triggered "in coincidence" with the energy deposited in the Tracker, and the event is rejected as a cosmic ray), a Calorimeter (that measures the particles' energies, and therefore the photons' energies) and a Data Acquisiton System (figure 1).

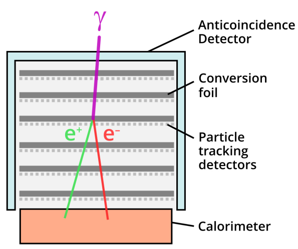

Figure 1. Schematic view of the LAT detector. Credits: NASA's Goddard Space Flight Center.

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Gamma-ray Burst Monitor (GBM)

The GBM detects photons of lower energies, including X-rays and gamma-rays in the range 150 keV - 30 MeV. It consists of 12 sodium iodide Low Energy (LE) detectors, oriented in different directions to track all the sky, bismuth germanate High Energy (HE) detectors (figure 2) and a Data Processing Unit [3]. As opposed to LAT, which maps the sources of the highest energy radiation, the GBM has the role to detect bright flashes of gamma-rays, providing fast information on the approximate position of the source.

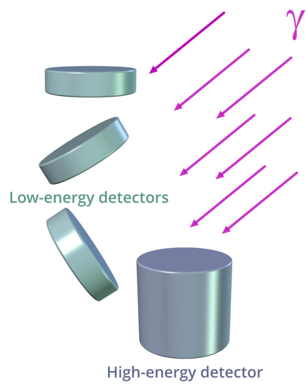

Figure 2. High and Low Energy detectors on the GBM face. Credits: NASA's Goddard Space Flight Center.

2 Data Analysis and Modelling

2.1 Access to *Fermi*'s Data

The NASA website[1] provides public access to *Fermi*'s data. They are given in event files, containing information on the gamma and background cosmic rays detection, and spacecraft files, with measurements of the position and orientation of the spacecraft during the detection. In the case of the LAT instrument, discrete events are recorded, and the reconstructed direction and energy for each event are created. Event files consist of photon and extended files, the latter with additional information about each event. Both event and spacecraft files are essential to extract physical meaning from photons arriving at *Fermi*.

We could obtain the files by specifying the sources' names or coordinates. We also had to define the search radius (given in degrees), which corresponds to the search cone opening angle, the observation dates and the energy range, so that only the relevant photons would be selected, keeping in mind the characteristics of the sources and the *Fermi*'s energy thresholds.

Data from an AGN (source name: "PKS 2155-304 source") and a GRB (source name: "GRB 130427A") were analysed. For both sources, the search radius was set to 20 ^{o} and the energy range to $[0.1, 500]$ GeV, imposing a range including HE and Very High Energy (VHE) photons ($E > 10$ GeV and $E > 100$ GeV, respectively). A region cone must be selected because, due to the low angular resolution of gamma-ray detectors, photons coming from different sources are mixed in the same spatial region. Therefore, to understand which photons are actually associated to our sources, we need to model the image of the whole field, taking into account the instrument response to incoming radiation.

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

The AGN source was studied using 1 year of filtered photon triggers (from 27/07/2013 to 27/07/2014 in the Gregorian calendar), while for the GRB source only 1 day of extended observations was needed (27/04/2013 in the Gregorian calendar).

2.2 The Fermitools

The Fermitools is a suite of tools developed by the Fermi Science Support Center (FSSC) and the instrument teams to analyse *Fermi* data, once they are distributed through NASA's website.

The data extraction was followed by the data preparation, in which the Good Time Interval (GTI) is defined using a LAT data configuration script that receives as input the data and spacecraft files. The GTI is the period when the conditions of detection were good. Those, and therefore the selection of the GTI, are mainly affected by solar flares, the vicinity to South Atlantic Anomaly charged particle excess and the position of the source with respect to Earth (sources cannot be observed when they are too close to the atmosphere). Thus, the configuration script provides a fundamental data setup for the following modelling stages.

Modelling was performed via maximum likelihood estimation methods, with a Test Statistic defined as $TS = -2\ ln(L_{max,0}/L_{max,1})$, where $L_{max,0}$ is the maximum likelihood value for a model without an additional source (the "null hypothesis") and $L_{max,1}$ is the maximum likelihood value for a model with the additional source at a specified location [4]. Thus, TS increases monotonically with $L_{max,1}$, which means that for larger TS the null hypothesis is incorrect (i.e., a source really is present).

The data setup delivered a description of the sources in the Region of Interest (ROI), which has more sources than the one we were interested in studying. To model the region properly, only the parameters of the more significant sources, with TS > 35, were set free to vary. When modelling the desired source exclusively, all other sources' parameters were set fixed. This distinction was particularly important in the AGN study, due to the existence of many sources and background light.

Models consider the average properties of the sources detected during all the period of data collection, from start of *Fermi*'s operation up to catalogue build process. However, the model "scales" these average properties to the selected duration of the observation. Those are the model starting parameters. When the fit was run, the free parameters were further adjusted, while the others kept their original values.

Active Galactic Nucleus's Analysis

The first stage of the AGN study was carried out using a binned analysis. One year of observing time implies that many photons arrive at the LAT, so there was the need to gather the photons in bins of the same energy or of the same detection time. The binned analysis is not as precise as the unbinned one, for we cannot distinguish the individual characteristics of the photons, but it provides a more computationally efficient analysis for the amount of available data.

The count maps of figure 3 represent the number of photons detected from points in the ROI, in celestial coordinates, with the chosen source lying at the center of the map. They show a higher brightness in the center, which reflects an efficient detection of the source, but so as for a few nearby sources and background light (due to the long observing time). The map on the right exhibits some sources that do not appear as clear in the data count map of the left (bottom left of the maps, especially). This is due to the fact that the model uses information obtained from a longer observation period, which results in a better contrast of the sources above the detector noise fluctuations. Thus, the left plot has a granular appearance, corresponding to real counts, while the map on the right looks smoother (mathematical representation of the same counts).

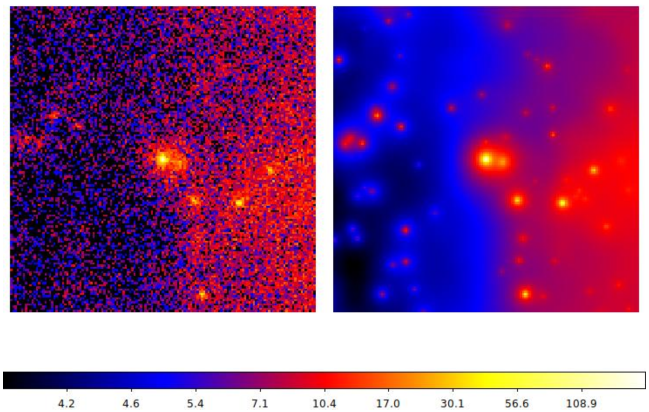

Figure 3. Count maps of the PKS 2155-304 source in celestial coordinates. On the left: map of photon counts over the year of observation. On the right: model using *Fermi*'s working time data (~ 10 years) "scaled" down to 1 year of "modeled" observation.

After confirming a good detection of the source, we could obtain light curves by letting only its parameters vary. A good balance to study the light curve evolution and working with a sufficient number of photons could be achieved by creating a weekly averaged light curve, that therefore required an unbinned analysis process.

Figure 4 shows a prominent blazar flare that lasted approximately from week 40 to week 45 of the observed year, with a maximum photon flux of $\approx\ 6 \times 10^{-7}\,\mathrm{ph\,cm^{-2}s^{-1}}$, on week 43.

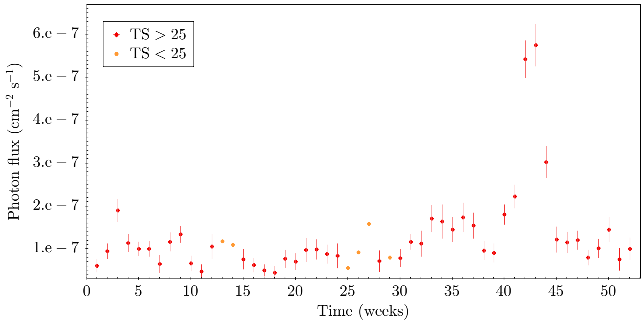

Figure 4. Full-year light curve, weekly averaged. TS ≡ Test statistics. Only detection with TS > 25, roughly corresponding to 5 times the background root mean square, are generally considered reliable in standard LAT analysis.

A more detailed light curve, over the days covering the four brightest weeks (week 40 to week 43), is shown in figure 5, confirming a more intense activity on day 22, at the start of week 43.

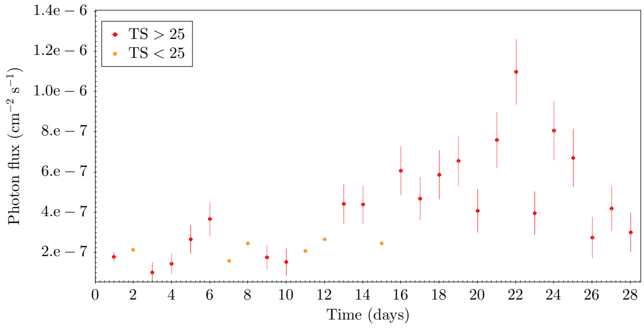

Figure 5. Light curve of the brightest weeks (week 40 to week 43), with a daily averaged photon flux.

We then fitted the spectral energy distribution (SED), both the full-year's and the brightest week of the flare's. The average SED arose from a binned analysis and the flare SED from an unbinned analysis, like the light curves. The fits are shown in figure 6 and were ran with a Log-Parabola model, given by

$$\frac{dN}{dE} = N_0 \frac{E}{E_b}^{-(\alpha+\beta log(E/E_b))}$$

where α and β contribute to the spectral index and E_b is a scale parameter that should be set near the lower energy range of the spectrum being fit and is usually fixed [5].

One sees that, on average (plot in blue), the flux starts decreasing and is less significant for higher energies. During the brightest week of the flare (plot in red), the source shows an increasing flux tendency with energy, with a relative increase of HE photons, with respect to LE ones, an effect called spectral hardening. These spectra also show that the *Fermi*'s capture of VHE photons is scarce in short events. On average, these photons exist, but we cannot tag them in a single flare.

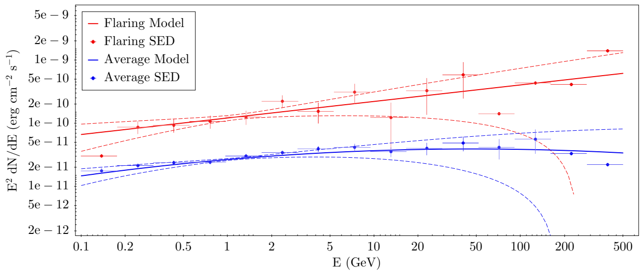

Figure 6. Full-year average and the brightest week (week 43) SED. The dashed lines represent the uncertainty limits of the model.

The possibility to select photons from higher energies over the observing time, shown in figure 7, corroborates the analysis of the SED results. The flare period, limited by the red lines, reveals a denser HE photon detection and the reach of energies a few greater than 250 GeV.

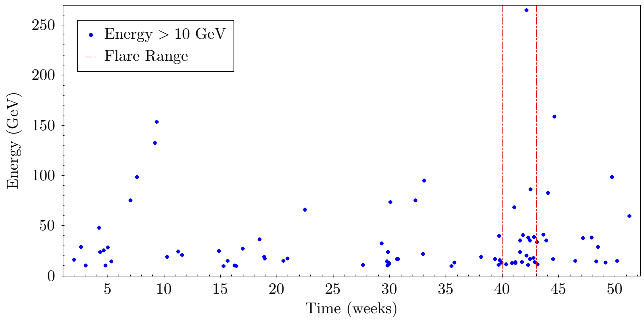

Figure 7. Full-year HE photons

Gamma-ray Burst Analysis

The GRB study was executed with an unbinned analysis from the beginning, since data corresponded to only 1 day of observing time, so there were very few background photons and sources to consider, compared to the AGN's.

The photon count map of figure 8 has the highest counts almost exclusively clustering towards the center, which is again explained by the fact that the GRB's low observing time does not allow the detection of many background photons and other sources.

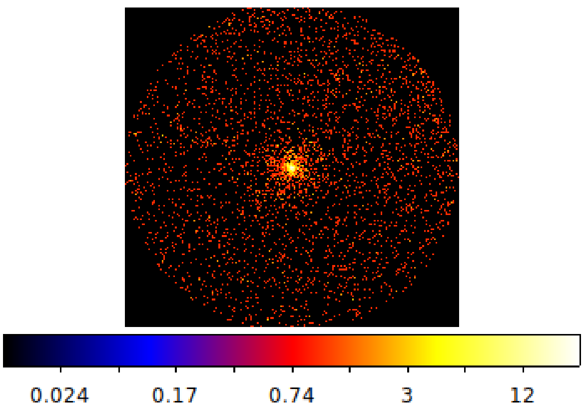

Figure 8. Photon count map of GRB 130427A over the day of observation.

From the light curve over the day of observation (figure 9), we infer the occurrence of a flaring event around hour 8, with a prominent flare with ≈ 70 photon counts. We notice that the burst appears as a sharp peak quickly followed by a second peak of ≈ 20 photon counts. Figure 10, with a smaller time scale, shows it more distinctively. The interpretation is that the source releases a jet of relativistic particles at the center of the star or system of stars (first peak); after a few minutes of travelling, this jet slams into material at rest and gives rise to the second, less bright, but more energetic peak.

A future more precise analysis (perhaps with a smaller time scale) between hour 7.8 and hour 8.1 could give us some information about *Fermi*'s ability to detect these type of rapidly successive events.

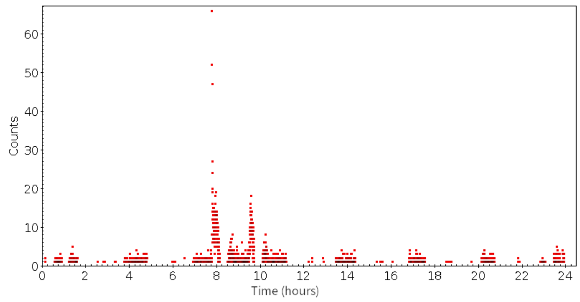

Figure 9. Light curve of the day of observation.

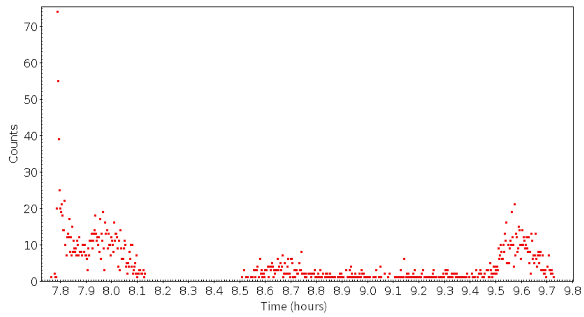

Figure 10. Light curve of the flare period.

Similarly to the AGN's SED, figure 11 exhibits a hard spectrum during the flare period, with an increasing flux tendency, though not very significant for higher energies (the model does not cover the last point).

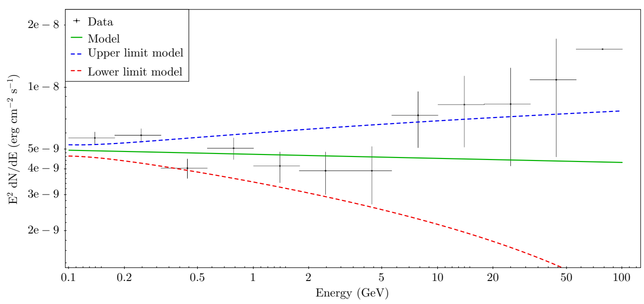

Figure 11. Flare period SED (between hour 7.75 and hour 9.73).

3 Challenges and Future Detectors

VHE photons are not easily detected by *Fermi* in short events, such as a flare, although they exist on average. The study of an AGN flare demonstrated that the source increased its luminosity by a factor of 3 for some weeks, and achieved a peak flux of 10 times the average for 1 day, increasing the production of HE photons. Energetic photons were also detected in the late emission of the investigated GRB, though with lower confidence, due to the shorter duration of the transient.

Investigating the properties of transient VHE emission through a monitoring instrument like *Fermi* helps us understanding what performance needs to be achieved by a new detector covering this spectral range. These studies indicate that the energy threshold of the next ground-based observatory should be as low as 100 GeV.

Acknowledgements

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References

[1] A.D. Angelis, M. Pimenta, *Introduction to Particle and Astroparticle Physics* (Springer International Publishing AG, part of Springer Nature, Gewerbestrasse 11, 6330 Cham, Switzerland, 2018)

[2] NASA, *Exploring the extreme universe*, `https://www.nasa.gov/content/goddard/fermi-spacecraft-and-instruments`

[3] NASA, *Fermi spacecraft and instruments*, `https://www.nasa.gov/content/goddard/fermi-spacecraft-and-instruments`

[4] NASA, *Likelihood overview*, `https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone`$_L$*ikelihood/Likelihood*$_o$*verview.html*

[5] NASA, *Source model definitions for gtlike*, `https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source`$_m$*odels.htmlLogParabola*