Gamma-ray Astrophysics with Current and Future Detectors

Camila Costa & António Maschio
Supervisors: Ruben Conceição, Giovanni La Mura

LIP | Laboratório de Instrumentação e Física Experimental de Partículas

September 10, 2020

Table of Contents

1. Gamma-rays Sources and Detection

Gamma-ray Bursts (GRBs)

The most energetic explosions in the Universe, thought to be created by the death of massive stars and merging binary neutron stars.

Fig. 1: GRBs animation frame. Credits: NASA's Goddard Space Flight Center.

Active Galactic Nuclei (AGN)

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.

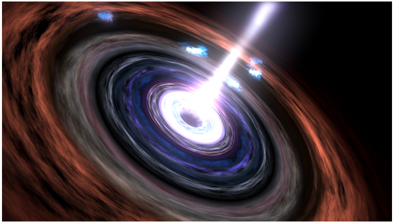

Fig. 2: AGN animation frame. Credits: NASA/Goddard Space Flight Center Conceptual Image Lab.

1. Gamma-rays Sources and Detection

Binaries

Two or more stars that orbit about their common center of gravity. Only some of these emit high energy gamma-rays.

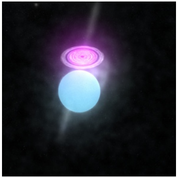

Fig. 3: An artist's conception of a microquasar system and its associated jets. Credits: NASA's Goddard Space Flight Center.

Pulsars

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 as radiation, mostly gamma-rays.

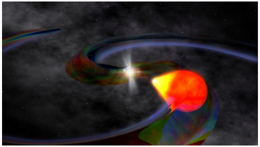

Fig. 4: Artist conception of a millisecond pulsar. Credits: NASA.

Supernova remnants (SRs)

Result from the most powerful explosions in the Universe and have a specially great impact on their host galaxies' chemical enrichment and evolution.

Fig. 5: Image data Chandra X-ray, DSS Optical and VLA radio. Credits: Chandra X-ray Observatory.

1. Gamma-rays Sources and Detection

Fermi Gamma-ray Space Telescope (*Fermi*)

Fermi is a spacecraft that orbits the Earth, launched June 11, 2008, with the purpose of studying the most extreme environments in the Universe (with energies impossible to reach on Earth), from black holes behaviour to the nature of Dark Matter and the origin of cosmic rays.

1. Gamma-rays Sources and Detection

Fermi instruments

Large Area Telescope (LAT):

- Primary instrument;
- Measurements using $\gamma \rightarrow e^{+}e^{-}$ conversions;
- Energy range: $30\ MeV - 500\ GeV$;

Gamma-ray Burst Monitor (GBM):

- Projected to detect ~ 200 GRBs per year;
- Energy range: $150\ keV - 30\ MeV$;

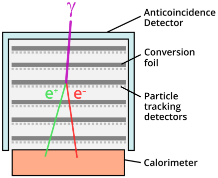

Fig. 7: Cross-section of the LAT. Credits: NASA's Goddard Space Flight Center.

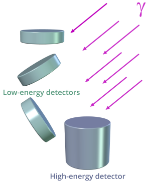

Fig. 8: Low-energy detectors on GBM face. Credits: NASA's Goddard Space Flight Center.

2. Data Analysis and Modelling

How to access data?

Fermi data are available on the NASA website[1], where the source of interest must be specified. Data are given in:

- **Event files** - gamma and background cosmic rays detection;
- **Spacecraft files** - position and orientation of the spacecraft;

Fermi's ability to track gamma-rays depends on the combination of these two types of information. Without the spacecraft data, event data have no physical meaning.

Data preparation:

- **Data selection** (e.g., to define the good time interval);
- **Analysis and modelling** (e.g., to map the number of photons detected, to bin data and to model them.)

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

2. Data Analysis and Modelling

Modelling is performed by **maximum likelihood** methods. To model the Region Of Interest (ROI), only the parameters of the more significant sources, with high test statistics ($TS > 35$), must be set free to vary. When modelling the desired source exclusively, all other sources parameters must be set fixed.

AGN Source - PKS 2155-304

1 year of observing time means many photons to analyse

$\Downarrow$

Binned analysis - less precise, but more computationally efficient.

Once we have general information about the source, we can proceed with the **unbinned analysis** to study specific time or energy ranges.

2. Data Analysis and Modelling

Count maps

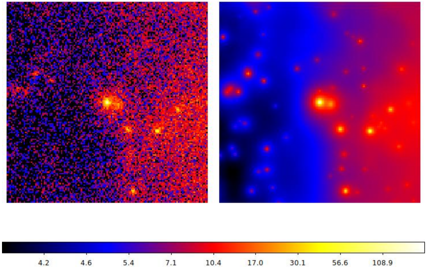

Fig. 9: On the left: map of photon counts over the year of observation. On the right: model using *Fermi* working time data ($\sim$ 10 years).

Higher brightness in the center of the map shows an efficient detection of the source, but so as for a few nearby sources and background light (due to the long time observation).

2. Data Analysis and Modelling

Light Curve

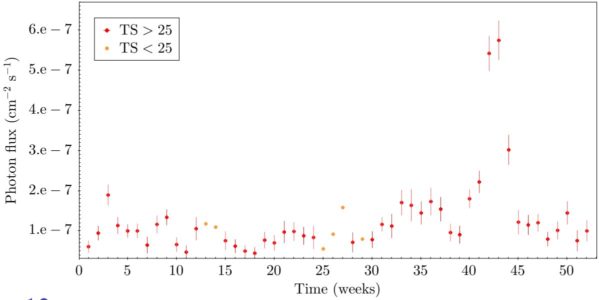

Fig. 10: Full-year light curve, weekly averaged. TS $\equiv$ Test statistics.

Prominent blazar flare that lasted approximately from week 40 to week 45, with a maximum photon flux on week 43.

2. Data Analysis and Modelling

Spectral Energy Distribution (SED)

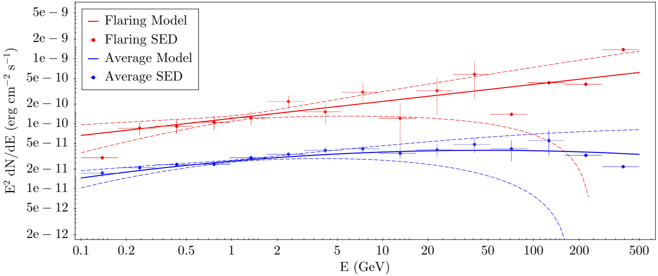

Fig. 11: Full-year average and the brightest week (week 43) SED.

On average, flux starts decreasing and is less significant for higher energies. During the brightest week of the flare, the source produces more high energy (HE) photons than low energy ones, an effect called **spectral hardening**.

2. Data Analysis and Modelling

HE Photons

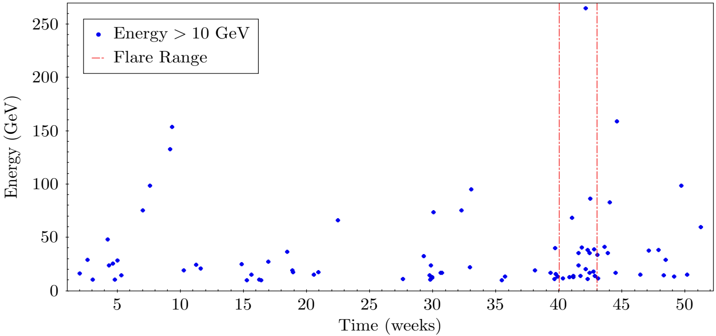

Fig. 12: Full-year HE photons.

The flare period reveals a denser HE photon detection and the reach of a few more than 250 GeV, which agrees with the previous SED results.

2. Data Analysis and Modelling

GRB Source - GRB 130427A

1 day of observing time

$\Downarrow$

unbinned analysis from the beginning.

Modelling is easier than for the AGN source, because there are less background photons and sources to consider.

2. Data Analysis and Modelling

Count map

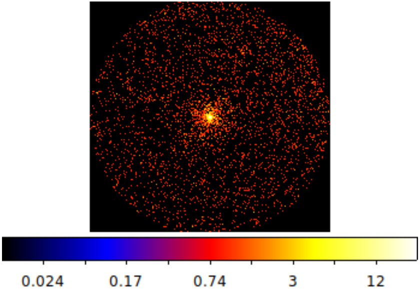

Fig. 13: Map of photon counts over the day of observation.

The highest counts are almost exclusively clustering towards the center - the GRB's low observing time does not allow the detection of many background photons and other sources.

2. Data Analysis and Modelling

Light curves

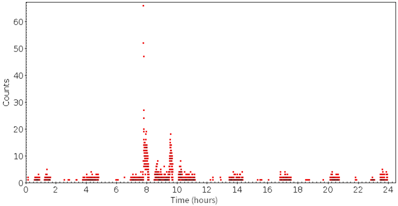

Fig. 14: Average full-day light curve.

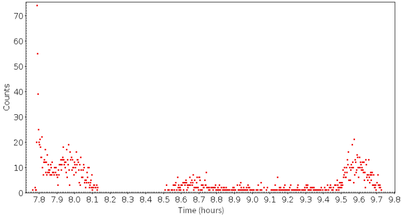

Fig. 15: Flare period light curve.

Flaring event around hour 8, with a prominent flare (> 60 photon counts) quickly followed by another (≈ 20 photon counts). A future more precise analysis, 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 successive events.

2. Data Analysis and Modelling

SED

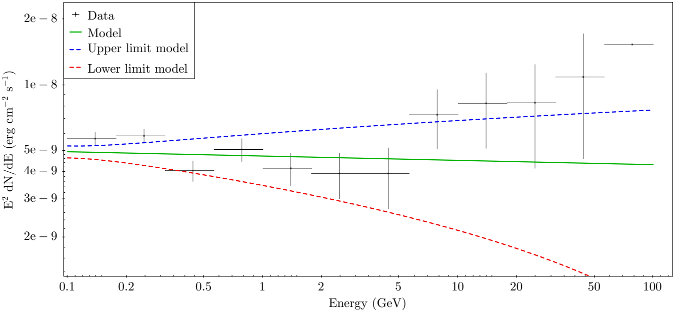

Fig. 16: Flare period SED (hour 7.75 until hour 9.73).

The flare shows a **hard spectrum**, with an increasing flux tendency, though not very significant for higher energies (the model does not cover the last point).

3. Challenges and Future Detectors

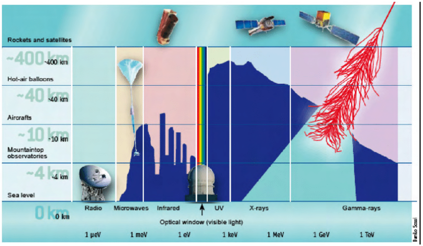

Fig. 17: Transparency of the atmosphere for different photon energies and possible detection techniques. Source: A. De Angelis and L. Peruzzo, "Le magie del telescopioMAGIC," Le Scienze, April 2007

Very high energy (VHE) photons are not easily detected by *Fermi* in short events, such as a flare, although they exist on average. 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.