2016 Fermi Masterclass

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This document briefly describes the proposed material to be presented to the students in the 2016 Fermi-LAT Masterclass dedicated to "Black Holes in the Universe". The Masterclass is aimed at 12th-grade students with good knowledge of physics. The emphasis is put on two violent cosmic phenomena that can be observed with the Fermi LAT and involve black holes of different sizes: blazars and gamma-ray bursts. It refers to the presentation posted at:
ftp://www.cenbg.in2p3.fr/astropart/VM/Masterclass_2016/Masterclass_2016_eng.pptx

The data used in the exercise can be downloaded (e.g., using wget) from:
ftp://www.cenbg.in2p3.fr/astropart/VM/Masterclass_2016/data_masterclass_2016.tar.gz

Introduction

The goal of the exercice is presented, namely "getting some familiarity with black holes and figure out how they manifest themselves in the spatial gamma-ray Fermi-LAT telescope". The agenda is briefly described at this point.

Background on black holes
Blazars, gamma-ray bursts

What is a black hole?

One first introduces the concept of escape velocity ($v = \sqrt{2GM/R}$). For a massive body, this is the initial velocity required for an object located on its surface to escape to infinity. It is 11 km/s for the Earth. Making the body either more massive or denser increases the escape velocity, until this speed ultimately reaches the speed of light, which cannot be overcome. When this happens, the object has become a black hole. The definition of a black hole (name coined in 1967 by Wheeler) is thus a body so dense (or compact) that nothing, even light, can escape from it. The region of no-return surrounding the black hole is called the "event horizon".

Historically, a black hole corresponds to a solution of Einstein Theory of General Relativity, describing gravity as an effect of curvature of space (and time) due to the presence of a massive body. *"Spacetime tells matter how to move; matter tells spacetime how to curve."* (Wheeler).

It was a long-standing question as to whether black holes existed in the Universe. Now we know for sure that they do exist and come in different sizes.

Exercise: From the above equation, calculate R for $v = c$ and M the mass of the Sun, $M = 2 \times 10^{30}$kg ($G = 6.67 \times 10^{-11}$ m^3 kg^{-1} s^{-2}). Answer R=3 km, radius of the event horizon for a solar-mass black hole.

Examples of space curvature: gravitational rings

A foreground galaxy acts as a converging lens for light rays emitted from a background galaxy. The image of the latter is distorted and appears as rings, called "Einstein rings".

Effect of gravitation on time

In addition to space, time is affected as well by gravitation (hence the term spacetime). A clock placed close to a massive object runs slower than another one placed far away. Gravitational time dilation

If this effect were not taken into account, the GPS system would not work accurately.

The central black hole of the Milky Way

The Sagitarus A* black hole ($\simeq$ 4 million solar masses) sits at the center of the Milky Way. Its mass can be assessed from the motion of nearby stars. It is believed that most large galaxies harbor central "supermassive" (from millions to billions solar-mass) black holes.

Why is a black hole not a giant vacuum cleaner swallowing the entire Universe?

Only matter (or light) crossing the event horizon is lost forever to the outside world. Like the stars orbiting at relatively large distances around the Milky Way central black hole, an observer can perfectly get fairly close to a black hole and escape unscathed as long as they stay outside the event horizon (the raius of the event horizon is 3 km for a one solar-mass black hole).

Gravitational Waves The spacetime can be made to vibrate when two massive bodies fuse together and emit "gravitational waves". The discovery of these waves, produced by the fusion of two 30-solar-mass black holes into a bigger one, was announced by the LIGO team in last February.

Galaxy, active galaxies, blazars

Definitions

- **Galaxy**: Group of hundreds of billions of stars. Our Galaxy is called the Milky Way and includes about 200 billions of stars. It is estimated that about 100 billions galaxies live in the Universe.
- **Active Galaxy:** galaxy with a very luminous inner part. Supermassive **black hole** pulling in matter (gas, dust) from a surrounding disk. Part of the infalling matter can be ejected through a high-speed (close to the speed of light) jet detectable in radio (radiogalaxies)

  Show the example of the closest (14 Mly) active galaxy Centaurus A, seen in the optical (galaxy seen side-on) and in radio (jett)..

  Show the example of NGC 4261, with the jet (radio) emanating from the black hole and a disk of gas and dust feeding a central (hidden) black hole.
- **Blazar:** radiogalaxy whose jet is directed towards Earth. The radiation is "beamed", that is focused in the jet direction. This leads to an amplification of the galaxy luminosity and the energy of its radiations. A blazar is a big cosmic machines (the biggest in the Universe): The black hole is the engine, the dust and gas of the disk is the fuel, the jet spouted out in the vicinity of the black hole transports the mechanic power away.

Life and death of a star

A star is like a big nuclear furnace, where light nuclei merge together to form heavier nuclei (fusion) releasing a large amount of energy.

The more massive the star, the heavier the nuclei it can produce by fusion reactions, but also the shorter its lifetime (10 billion years for the Sun, 30 million years for a star 10 times as massive).

The star lives as long as it has enough light nuclei to transform. A balance between gravity and the pressure arising from the energy production in the inner part prevails. As the star progressively runs out of fuel, it becomes hotter at the center to maintain that balance.

When the star has exhausted its supply of light nuclei, the balance is disrupted so much that the star core will collapse. For not too massive stars, effects related to the ("quantum") nature of elementary particles will come into play and halt the collapse (electrons and neutrons dont like to be squeezed too much). Depending on their masses, dying stars will end up into:

- white dwarfs (for stars like the Sun);
- neutron stars (for heavier stars);
- black holes (for the heaviest stars, when no processes can halt the collapse).

Very massive stars die in gigantic explosions giving birth to a black hole and ejecting a very fast jet of matter: this is a (long) gamma-ray burst (detectable as a flash of gamma-rays). A tremendous amount of energy is released during this event.

The Milky Way harbors a few tens millions of stellar-sized black holes but since they don't shine, most of them lurk unseen. Only the existence of about twenty of these black holes have been established, as they are members of binary systems.

Background on gamma-ray astronomy

Exercise: From $E=k_BT$, estimate the temperature for E=1 MeV ($k_B= 1.4\times10^{-23}$ J.K^{-1}). Answer: $T = 1.2\times10^{10}$K. This temperature is unphysically high. Gamma-rays are produced by "non-thermal" processes.

In blazars and gamma-ray bursts, particles (electrons or protons) are accelerated to very high energies (>10 GeV) in the jet.

Gamma-rays can only be produced by high-energy particles. Their detection allow the study of the *cosmic particle accelerators* in the Universe:

- Active galactic nuclei (as blazars, very time variable).Particles (electrons or protons) are accelerated to very high energies (>10 GeV) in the jet.
- Gamma-ray bursts (life-ending explosions of very big stars producing a very fat jet and lasting a few seconds).Particles (electrons or protons) are also accelerated in the jet.
- Pulsars (fast-spinning neutron stars, which are the collapsed cores of large stars remaining after supernova explosions)
- Supernova remnants, the ejecta some of them accelerating the cosmic rays that bombard the Earth.

The high-energy particles emit radiations, including gamma rays, by interacting with

- matter,

- other radiations,
- and magnetic fields.

The gamma-rays are blocked by the atmosphere: a telescope on board a satellite is required to detected them. The radiation is so faint that one detects one light particle (a photon) at a time. One detects only about one photon every 10 s from the brightest gamma-ray source in the sky (the Vela pulsar).

Notions of flux and luminosity

The number of photons emitted in a cone per second remains constant and thus is independent of the distance to the source. At a given distance, the area of a sphere intercepting the cone scales as the square of the distance. So the number of photons per square cm and second (i.e. *the flux*) is inversely proportional to the distance squared ("inverse-square law").

- **Number of collected photons:** N= $F_p \times S \times T$
  N = Number of collected photons (measured)
  F_p =photon flux (photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)
  S = Collecting area (cm^2)
  T = Collecting time (s)
  The factor $S \times T$ is called "exposure". A telescope like the Fermi LAT works like a photographic camera: in both, the collected light depends on the exposing time and the collecting area (for a camera, the lens diameter, or more exactly the F/D ratio).
- **Photon flux:** $F_p = N/(S \times T)$
- **Energy flux** F_E= $F_p \times \overline{E}$
  F_E= Energy flux (W cm^{-2})
  $\overline{E}$= Mean measured photon energy (J). 1 MeV= 1.6 10^{-13}J
- **Fluence** (total collected energy/cm^2): F= $N \times \overline{E}/S$
  F= Fluence (J cm^{-2})
  $\overline{E}$ = Mean measured photon energy (J)
  N = Number of collected photons (measured)
  S = Collecting area (cm^2)

- **Source luminosity** $L = 4\pi \times d^2 \times F_E$
  L = Luminosity (W)
  d = source distance (cm).

For orientation the Sun Luminosity is 4 10^{26} W and the Milky Way luminosity is 5 10^{36} W.

Exercise: The Sun luminosity is 4×10^{26} W. Estimate the Sun energy flux at Earth (distance =150 Mkm). Answer: 1.4 kW m^{-2}.

Different parameters characterize a celestial object emitting radiations:

- Its sky position (two coordinates, which are angles similar to the longitude and latitude on Earth).
- its flux (possibly variable in time). Unit: photon cm^{-2} s^{-1}
- its "flux density" also called "spectrum", representing the weight of the different detected radiations as a function of their energy. It is a flux per energy unit.

In the gamma-ray energy domain, the flux density can often be modeled by a power-law function $N(E) = kE^{-a}$ where k and α are constants α is called the spectral index.

The Fermi-LAT telescope

The Large Area Telescope on board the Fermi satellite was launched by the NASA on June 11, 2008. It is a "pair-Conversion telescope", detecting a light particle called photon at a time. These photons have large energies, typically greater than 100 MeV, which makes them gamma rays. The gamma-ray photons interact with matter and produce an electron-positron pair. This effect derives from Einstein's famous formula ($E=mc^2$). Pure energy (the photon) is converted into matter with a measurable mass (the electron-positron pair).

The LAT is hence a detector very similar to those used in particle physics at CERN. A LAT prototype was incidentally tested at CERN prior to launch. On top of gamma-rays, the LAT also detects charged cosmic rays (over 1000 times more abundant than gamma-rays). Sophisticated methods are used to disentangle the two species of particles. These methods do not work with a 100% efficiency. Sometimes gamma-rays are unduly rejected, leading to a detection efficiency less than 100%.

Effective (Collecting) area

This area is the geometrical area times the detection efficiency, hence the term "effective area". It depends on the energy (since so does the rejection efficiency) and the angle between the gamma-ray direction and the detector axis. If the detector was infinitely thin and recorded all particles hitting it, the collecting area would scale as the angle cosine.

Angular resolution

A point source in the sky does not show up as a unique photon direction in the data, but as more or less extended cone (or spots in the maps). The telescope has a limited precision when measuring the photon arrival direction (angular resolution). This precision is about 1 degree for a 100 MeV photon but improves at higher energies.

Background rejection

Goal After a quick training, try to tell from the event displays whether the primary particles are most likely photons or charged cosmic rays (to be developed). Guess the energy: Low, medium, high?

The Fermi-LAT data

The data are freely available from the public NASAs Fermi-LAT data server. It usually takes less than 12hr between their collection onboard the spacescraft and their being posted on the server.

Explore a weekly data file with the command fv (fits viewer)

> *fv fits_file/lat_photon_weekly_w074_p302_v001_filt.fits*

Each row represents a photon and the columns correspond to the associated parameters. In the follwing, we will only use the following parameters: two direction coordinates, giving the sky location of the photon source, the time of arrival (in Mission-Elapsed Time, starting 1970, Jan. 1st) and the photon energy (in MeV).

Creation of sky maps

Two coordinates are needed to locate a point in the sky, equivalent to longitude and latitude at the Earth surface. They are called right ascension (equivalent to longitude), and declination (equivalent to latitude).

Description of the sky seen by Fermi in (equal-area) Hammer-Aitoff projection
The diffuse background is made of photons coming from the interaction of cosmic rays with matter (dust, gas) present in the Milky Way. Point sources are also visible.

It is cool to create the current sky map using the latest available data. After fetching the latest data (> *fetch current*) and noting the current week number, the map is displayed with the following command:
> *create_map #week (option)*
option= cel, gal, ait (different sky projections)
Example: > *create_map 429 ait*

Study of a blazar outburst

3C 454.3 is the brightest blazar among the thousands detected by LAT. Blazars are radio galaxies (belonging to the class of active galaxies) exhibiting a relativistic jet emanating from the regions near a central supermassive black hole (with a mass exceeding 100 milion solar masses) and directed straight to the Earth. This feature makes the source very bright and leads to very variable emission within the cone spanned by the jet. Located 7.2 billion light years away (redshift=0.859) and hosting a 4-billion solar mass black hole, 3C 454.3 showed several major eruptions since the commissioning of Fermi in August 2008, the most spectacular one taking place between 17 and 22 November 2010 (week 128). The source, with celestial coordinates (RA, DEC)=(343.5°,16.15°) was the brightest object in the sky in that period.

Goal: Determine the peak luminosity of the blazar during the outburst, and compare it to the Milky Way luminosity.

To get insight into the flare, one creates a light curve for 3C 454.3 during weeks 128 and 129:
> *create_light_curve 128-129 lc_3454.txt 0 0 86400 343.5 16.15 5*

We will focus on the 3-day period (Nov. 18-19-20) when the source is the brighter. One creates a 15°-in-radius map centered at 3C 454.3 position, from 00:00 UTC 2010, Nov. 18 (MET 311731200) to 00:00 UTC Nov. 21 (MET 311990400):
> *create_map 129 ait 311731200 311990400 343.5 16.15 15*

Here, one can recall the reason for the photon spread (angular resolution), making the point source look like a spot.

Options: Using data in csv format csv to make a map with Excel or other spreadsheet applications known to the students: Scatter plot or 2D histogram?

Rough estimate of the flux

Goal: In this part, the photon flux is estimated by "aperture photometry" via direct application of the equation: $F_p = N/(S \times T)$

Estimate the number of source photons:

1. In the WCS menu, select FK5 (celestial coordinate system).
2. Place the pointer at the source position. Left click and move the pointer away to increase the radius of the selected region (green circle) up to about 6°, (estimated from the underlying grid).
3. Click on *region* → *information* → *Analysis* → *statistics* and read off the number of photons within the region (about 10200)

Compute the exposure

> *create_exposure 129 map 200*

(Note: 129 is the week number, "map" is a flag requiring the use of the existent map created above, 200 is the energy in MeV at which the exposure is computed. This energy is chosen so as to give a value close to a typical spectrum-weighted average.)

One reads the exposure value off the map at the source position. It is about 1.65×10^8 cm^2 s.

Can we make sense of this value (order of magnitude)?

Effective area at 200 MeV and 0°: $\simeq$5000 cm^2
Effective area at a typical average angle of 30°: 70% of value at 0°
Total time: 3 days = 259200 s
Field-of-view: 20% of the whole sky
Exposure: S $\times T$=(5000*0.7)*(259200*0.2)= 1.8 $\times 10^8$ cm^2 s

Compute the flux

From $F_p = N/(S \times T)$, one gets: F_p= 10200/1.65 $\times$ 10^8 = 6.2 $\times$ 10^{-5} ph cm^{-2} s^{-1}

More accurate estimate of the flux

Goal: Use a tool taking into account the energy dependence of the effective area to get: the photon flux and the average photon energy. With these values and the source distance (1.7 10^{28} cm) determine the luminosity during the flare.

> *fit_spectrum 129*
Adjust the flux and spectral index of a power-law function so as to best match the data by eye. The right-hand panel displays the function used (top) and the exposure as a function of energy (bottom) whose product yields the number of photons as a function of energy (left-hand panel).

Best match (eye-fitted) values: Photon flux : 6.5 10^{-5} ph cm^{-2} s^{-1}
Spectral Index (α): 2.3
Mean Energy ($\overline{E}$) : 433 MeV = 433 $10^6 \times 1.610^{-19}$ = 2.6 10^{-11}J

One gets: Energy flux : F_E= $F_p \times \overline{E}$= 4.5 10^{-15} W cm^{-2}
and considering a distance of 1.7 10^{28} cm:
Luminosity $L = 4\pi \times d^2 \times F_E$ = 1.6 10^{43} W (=1.6 10^{50} erg s^{-1})
Recall: Milky way luminosity: $5{\times}10^{36}$ W

Conclusion: During this flare, 3C 454.3 was as bright as 3 million galaxies like the Milky Way!

Note In reality, the source does not radiate uniformely in all directions, but only in a cone of about 5-degree opening along the jet.

Study of a very bright gamma-ray burst

The gamma-ray burst GRB 080916C, probably related to the explosion marking the death of a very massive star and the birth of a black hole was detected on Septembre 16, 2008 at 00:13 UT (RA=120°, Dec=-56°). It lasted 23 minutes. The estimated distance of the event (redshift=4.35) was 12.2 billion light years. Its exceptional power corresponded to that of 9000 supernovae.

The publication in the Science journal on this event can be found at:

http://www.sciencemag.org/cgi/rapidpdf/323/5922/1688

Accounting for the expansion of the Universe, one calculates the following distance: $d = 1.25 \times 10^{29}$ cm.

Goal: calculate the total gamma-ray energy released during the explosion

Light curve

Once again, one selects the photons:

> *create_map 15 ait 243216700 243217000 120 -56 20*

They are stored in the following file:
fits_file/lat_photon_weekly_w015_p302_v001_temp.fits

One can create a movie of the event as:

> *python create_movie_scat.py file_fits/lat_photon_weekly_w015_p203_v001_temp.fits 20*

To display the movie:

> *firefox fits_file/mov_15.gif*

One can create a simple light curve as:

> *hist fits_file/lat_photon_weekly_w015_p302_v001_temp.fits TIME 600*

This figure can be compared to Figure 1 (panel 2 from bottom) of the Science paper.

Total released energy

We first compute the fluence by summing up the energy of all GRB photons and dividing by the effective area.

> *fluence 15*

Fluence: $N \times \overline{E}/S = \sum_i E_i/S$=80000 MeV/3000 cm^2=4.3$\times$10^{-12} J cm^{-2}

E$_{tot}$= 4 π d^2 Fluence /(1+z) = 1.6 10^{47} J

Note: Solar mass: $M_\odot$ = 2$\times$10^{30} kg. $E = M_\odot\ c^2$ = 2$\times$10^{47} J = 2$\times$10^{54} erg

Conclusion: The measured energy released in gamma-rays during this GRB corresponds to about one solar mass converted into energy!

For comparison, the yearly french electric-energy production corresponds to a mass of 20 kg.

The total worlwide energy production in 2013 was 13600 Mtep (1tep =41,855GJ), i.e., an equivalent mass of 6 tons.