Gammapy: high level data analysis for extragalactic science cases with the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) observatory will probe the non-thermal universe above 20 GeV up to several hundreds of TeV with a significant improvement in sensitivity and angular resolution compared to current experiments. Its outstanding capabilities will allow to increase the number of extragalactic cosmic accelerators detected at very high energy (VHE) and therefore to better constrain the population of VHE accelerators and the gamma-ray absorption processes in the intergalactic medium. For the first time in history of imaging atmospheric Cherenkov telescopes (IACTs), CTA will be an open observatory and high-level data will be made available to the astronomical community. Gammapy is an open-source Python package developed by the Cherenkov telescope community that provides tools to simulate the gamma-ray sky and analyse IACT data. The versatile architecture of, and steady user contribution to Gammapy enable a large variety of high-level data analyses. Examples of Gammapy applications are presented, particularly in the context of extragalactic science with CTA.

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1. Introduction

The next generation of Imaging Atmospheric Cherenkov Telescopes, the Cherenkov Telescope Array, will probe the γ-ray sky above 20 GeV with an unmatched sensitivity and angular resolution using more than 100 telescopes distributed on the South (Chile) and on the North (La Palma) sites. To reach this goal, three different types of telescopes will be used : the 23 m diameter Large-Size Telescopes (LST), the 12 m diameter Medium-Size Telescopes (MST) and the 4 m diameter Small-Size Telescopes (SST). They are respectively adapted to detect photons of 20 GeV–200 GeV (field of fiew of ∼4°), 0.1 TeV–10 TeV (field of fiew of ∼7°) and 1 TeV–300 TeV (field of fiew of ∼9°).

With its improved sensitivity and higher field of view compared to current experiments, namely MAGIC, H.E.S.S. and VERITAS, CTA will improve our current knowledge on active galactic nuclei (AGN) and especially on blazars. Nowadays, population studies are quite limited by the low/biased sample of blazars detected at very high energy ($E \geq 100$ GeV). The high quality spectral resolution of CTA will help to look for hadronic signatures in AGN spectra [1]. Furthermore, it will also help to better constrain the intergalactic medium opacity to γ-rays, and especially the flux density of the diffuse extragalactic background light (EBL). The first VHE detection of γ-ray bursts (GRBs) might shed light on the radiative processes and the particle content in those accelerators and might provide a new class of distant objects to constrain the EBL density.

CTA is expected to operate for thirty years and unlike actual experiments it will be an open observatory, meaning that high level data, such as event lists and instrument response functions (IRFs), will be made available to the scientific community. Gammapy[1] is a community-developed, open-source Python package for γ-ray astronomy [2]. It is built on widely-used scientific packages (Astropy, Numpy, Scipy) and provides tools to simulate and analyse IACT data. It was thought to produce high level data, such as spectra, maps, light curves and even catalogues, taking as inputs lower level data such as event lists and instrument response functions. Classical methods to analyse data in very high energy astronomy, such as background substraction or full-forward folding spectral reconstruction are implemented and were highly tested with real data, especially in the H.E.S.S. experiment. Cube-style analysis, in which a spectral and a spatial model are jointly adjusted, is also implemented (see [3]).

In this contribution, we show how Gammapy can easily be used to tackle some extragalactic science cases of CTA. We first present in Section 2 how point-like simulations are made within Gammapy. Section 3 describes how it can contribute to the ongoing efforts to estimate the number of expected blazars that could be detected with CTA. Section 4 is a technical discussion on how Gammapy can be used to constrain the EBL scale factor and finally, Section 5 briefly presents an application about GRBs detectability. Example scripts are made available in a dedicated repository[2].

2. Simulations

In the following, we will focus on point-like source simulations. To reach this goal, simulations are generated with a set of instrument response functions, which are produced by the simulation

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[1]http://docs.gammapy.org/en/latest/
[2]https://github.com/gammapy/icrc2017-gammapy-cta-egal

group in the consortium [4], including :

- effective area as function of true energy,

- background rate as function of reconstructed energy,

- energy migration matrix as function of true energy

An energy dependent angular cut is applied to maximise the significance in each interval of reconstructed energy. To compute an expected excess for a given spectral model and exposure we multiply the desired input spectra with the absorption of one of the available EBL model [5, 6, 7] in Gammapy. We sum the randomised expected excess and background counts to get the data in the ON region of the source. Finally, we randomised the background counts multiplied by the normalisation between the ON and the OFF regions, take as 0.2 in the following, to get the data in the OFF region. The average time to run 100 simulations is less than 900 ms on a personal computer[3]. In the following sections, the level of significance is estimated with the formula 17 of [8].

3. Application example : extrapolation of blazars from Fermi/LAT catalogues

The Fermi/LAT collaboration recently released the 3FHL (The Third Catalog of Hard Fermi-LAT Sources) catalogue [9]. It contains 1558 sources detected above 10 GeV in 84 months and analysed with the improved PASS8 analysis. The blazar dominates the sample of sources (78 %), followed by the galactic sources (9 %) and the unassociated ones (13 %). One of the main tasks of the extragalactic group of the consortium, in the preparatory phase, is to estimate the number of detectable AGN by CTA, using as a starting point the 3FHL catalogue, and to measure its impact on population studies. A realistic analysis is available in [10].

To illustrate Gammapy capabilities, we studied the impact, on the detection level, of adding an hypothetical exponential cut-off to the 3FHL Fermi/LAT spectra. We selected a sample of 466 blazars, firmly identified or associated BL Lacs or flat spectrum radio quasars (FSRQs), having a redshift estimation in the catalogue and whose meridian transit occurs with zenith distance less than $30°$ at least in one CTA site (north or south). We applied an exponential cut-off at $1\,\mathrm{TeV}/(1+z)$ to the Fermi/LAT spectrum. To assess the detection level of a source, the following procedure was used :

- the spectrum is absorbed by the EBL model [5]

- the IRF labelled as "5h", production 3b, are used according to the declination of the source ($\delta \geq 0$ is north site)

- the simulation is done for 20 h of observation

- the counts are integrated from 50 GeV to 100 TeV

- the final significance is averaged on 20 simulations

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[3]This estimation has been realised with the Timit Python package and a 2.9 GHz Intel Core i7 processor.
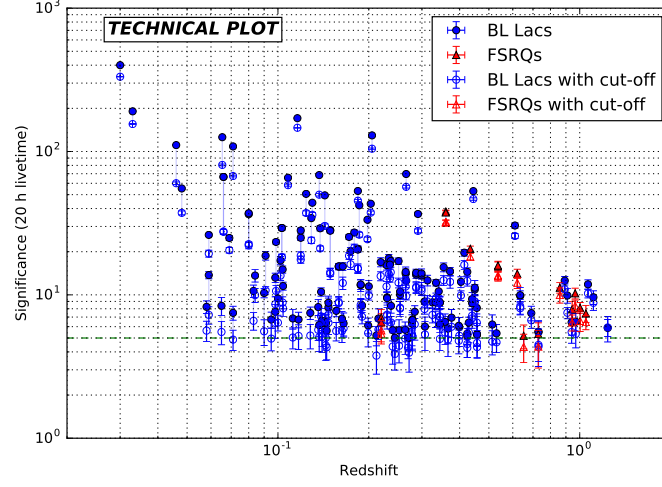
Figure 1: Average significance as a function of redshift for the simulated BL Lacs (blue circles) and FSRQs (red triangles). Full markers represent the 3FHL spectral model and empty markers represent the 3FHL spectral model multiplied by an exponential cut-off at $1\,\text{TeV}/(1+z)$.

The results of the simulations are shown on Figure 1. Respectively $\sim$53 % (151/290) and $\sim$10 % (15/156) of the selected BL Lacs and FSRQs are detected above 5σ. Adding the cut-off decreases theses numbers to 46 % and 8 %, showing the impact of the choice of the intrinsic spectral shape. An example script is available[4] and illustrates the simplicity of such studies with Gammapy.

4. Application example: the EBL scale factor

One of the main cosmological topics with the Cherenkov Telescope Array is to improve the constraints obtained with blazars on the diffuse extragalactic background light. A general and complete discussion can be found in [11]. In this section we will focus on the technical aspects to constrain an EBL scale factor for a given absorption model with Gammapy and the Python library Sherpa[5]. Gammapy has been designed to provide flexibility in data-analysis to the end users. Simulations can be fed to widely-used tools that have been developed for X-ray astronomy, such as the Sherpa library, to produce higher data level. Sherpa gives access to the full-forward folding method to handle spectral reconstruction and provides a convenient way to do arithmetic with spectral models. Furthermore, each model can be adjusted on its own dataset and each parameter can be linked between different models, which makes the fit of the EBL scale factor straightforward. To obtain strong constraints on the EBL scale factor it is necessary to adjust multiple sources for different redshift ranges (see [11]). The choice of the modelling of the source will have an impact on our ability to reconstruct the EBL scale factor.

As an illustration, we studied the impact of an exponential cut-off, fixed at as $1\,\text{TeV}/(1+z)$, on the determination of the EBL scale factor, called α, for different redshifts. To proceed, we used the same sample of blazars described in [11] and adjust for each source the intrinsic spectra ϕ_{int} and
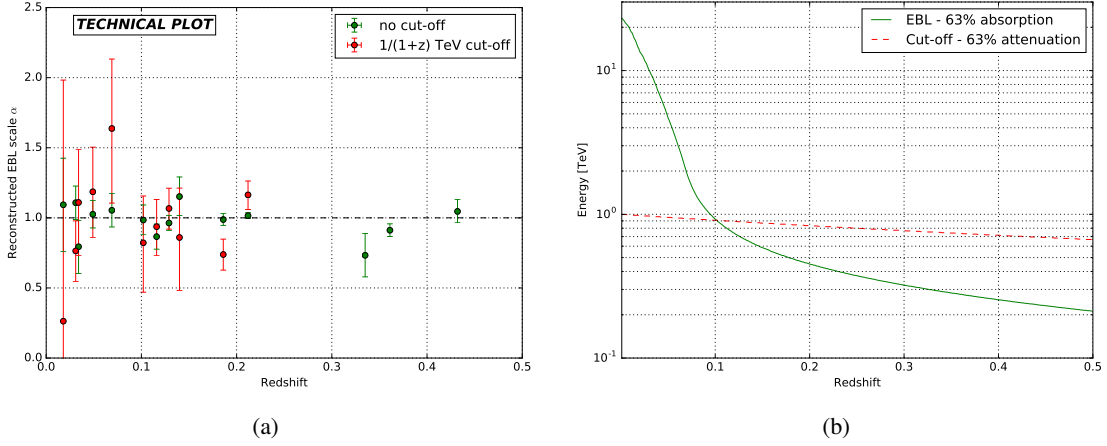
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[4]https://github.com/gammapy/icrc2017-gammapy-cta-egal
[5]http://cxc.cfa.harvard.edu/contrib/sherpa/

(a)   (b)

Figure 2: (a) Estimation of the reconstructed EBL scale α for individual sources used in [11] as a function of their redshift. The best estimation of alpha obtained without and with an additional cut-off on the intrinsic spectral model are respectively shown with green and red points. (b) The curves, displayed as a function of energy and redshift, corresponding to a loss of 63 % of the photons are respectively shown in green and red for the EBL absorption and the exponential cut-off attenuation.

$\alpha : \phi(E) = \phi_{\text{int}}(E) \times e^{(-\alpha \tau_m(E,z))}$ where τ_m is the γ-ray opacity of the intergalactic medium given by the model m. For each source, the following procedure was used to study the scale reconstruction without (with) a cut-off :

- the intrinsic spectra is given by the 3FHL catalogue, e.g. a power law or a log-parabola (and multiplied by a cut-off)

- the spectra is absorbed by the EBL model [5]

- the IRF labelled as "5h", production 3b, are chosen according to the declination of the source ($\delta \geq 0$ is north site)

- the simulation is done for 100 h of observation

- the spectra is fitted with the full-forward folding method in a fixed energy range from 50 GeV to 5 TeV, with the intrinsic spectra model (and multiplied by a cut-off)

- the confidence interval bounds are computed for each parameters

We show on the technical Figure 2a, the reconstructed scale α as a function of the redshift of the sources for the two different spectral models. For low redshift, $z \leq 0.1$, The EBL absorption begins in the energy domain where the exponential cut-off is already present (see Figure 2b) so it makes it harder to constrain the EBL scale factor (the error bars increase). This could be in part compensated by a higher number of sources at low redshift. For the intermediate redshift range, typically from $z \sim 0.1$ to $z \sim 0.2$, the two effects are competitive and we are able to distinguish the two components. At higher redshifts, the EBL extinction intervenes well before the exponential cut-off and the latter becomes less pertinent and thus under-constrained (for those cases, the max-imisation likelihood procedure fails). That shows that Gammapy, in connection with the Sherpa

library, is particularly well suited for this kind of studies. Example scripts are available on the Gammapy repository https://github.com/gammapy/icrc2017-gammapy-cta-egal.

5. Application example: observational window for γ-ray bursts

The γ-ray bursts are transient and explosive phenomena originating from cosmological distances. For the brief episode of emission their total energy output reaches 10^{51}-10^{53} ergs, placing them among the most powerful presently observed objects. A burst is characterised by a prompt phase dominated by X-ray and γ-ray photons (typically between 10 keV and a few MeV), lasting for a few ms to a few hundreds of seconds. It is followed by a second emission phase, called the afterglow, during which the electromagnetic emission is shifted to lower energies (X-rays, visible, radio) and rapidly decaying with time. The origin of the bursts is not fully understood. Nevertheless, the combination of the short variability timescale and the huge energy release suggest that GRBs accompany cataclysmic events in the Universe, most likely associated with the births of stellar size black holes or rapidly spinning, highly magnetized, neutron stars. Up to now, the Fermi/LAT detected more than 100 γ-ray bursts above 75 MeV, whereas IACTs never detected a significant γ-ray emission for these objects. With its high effective area and its big field of view, CTA might detect a few of these events and help to better constraints their intrinsic properties. To get a more detailed picture about high energy and very high energy GRBs the reader may refer to [12] and [13], respectively.

Here, we used Gammapy to reproduce the result showing the detection significance of the γ-ray burst GRB 080916C as a function of the observational window as in the study done by [14]. The spectral template of the bright γ-ray burst GRB 080916C is described as a power law of constant spectral index of 2 with an integrated flux in the 0.1 GeV–10 GeV range at a time t_p of $\Phi(t_p = 6.5\,\text{s}) = 500 \times 10^{-5}\,\text{cm}^{-2}\,\text{s}^{-1}$. We further assume that the GRB is located at a distance[6] corresponding to $z = 3$. The flux decay over time is parameterized by a decay index $\delta = 1.7$. In order to study the significance of the source as a function of the observational window, we defined 20 logarithmic time intervals representing the beginning and the end of the observations, from 20 s to 2 days. Starting from $t_0 = 20\,\text{s}$ after the peak flux, the significance was computed for each physical logarithmic time interval in the following way :

- the average time interval t_{int} is computed by taking into account the flux decay law

- the flux normalisation is computed for t_{int}

- the spectra is absorbed with the EBL model from [5]

- the North IRF, labelled as "0.5h" from the production 2 are used

- the counts are integrated from 30 GeV to 1 TeV

Results of the simulations are shown on Figure 3. They were obtained with only a few lines of code available on the dedicated repository[7].

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[6]The measured redshift of GRB 080916C is $z = 4.35 \pm 0.15$ [15].

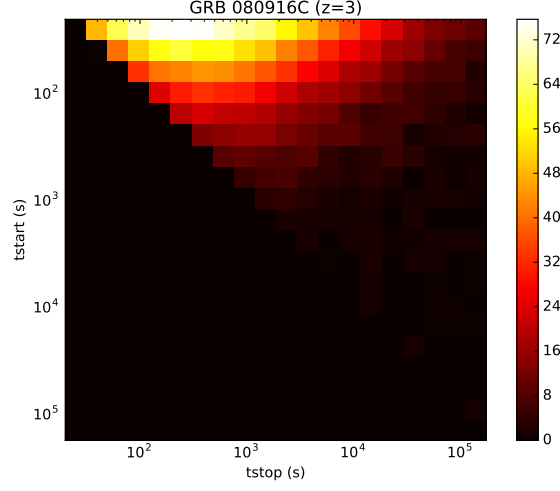[7]https://github.com/gammapy/icrc2017-gammapy-cta-egal

Figure 3: Significance of detection as a function of time windows for the template of GRB as described in the text.

6. Conclusion

This contribution showed how Gammapy capabilities can be used to handle extragalactic science cases with the Cherenkov Telescopes Array. In addition, we provided example scripts so that users experience themselves how extragalactic results can quickly be extracted with Gammapy.

Acknowledgments

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