Binary observations with the CTA gamma-ray observatory

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Abstract

The aim of the project is to study the sensitivity of CTA to high-energy emission from binary systems, consistent of a compact object and a massive star. The work imply high-level gamma-ray data analysis and toy Monte Carlo simulations, taking into account sources properties and the characteristics of the CTA observatory. The specific studied source is LS I +61 303, for which the light curve is extracted and fitted with suitable temporal model.

Contents

1 Introduction

The Very High Energy /VHE) gamma-ray Astronomy concerns energies above 100 GeV. Today, detectors are searching for particle accelerators in the universe, for which the gamma-ray emission might be dominated by leptonic or hadronic interactions. At very high energies, very few photons are expected: one gamma-ray photon per m^2 *per year* from a bright source or *one per* m^2 *per century* from a faint source [1]. The low number of photons represent one the main challenge for the detection.
For this reason, the principle is based on the detection of Extensive Air Showers induced by photons entering in the atmosphere and interacting through pair production, responsible for the Cherenkov radiation. The Imaging Air Cherenkov Detectors allow to observe the full shower development, with a good energy resolution and a better background rejection than other detectors. The disadvantage is that the field of view is very small and dark conditions only, with short exposures, are required. The first object at VHE, the Crab Nebula, was detected by the Whipple Telescope with the ON-OFF technique and it opened the window of VHE gamma-ray Astronomy. Today, instruments that are taking data are VERITAS, HESS and MAGIC and from 2022 also CTA.

2 The Cherenkov Telescope Array (CTA)

CTA is the next-generation of ground-based gamma-ray detectors, currently constructed on the Island of La Palma and in the Atacama Desert in Chile. Using more than one hundred telescopes between the southern and the northern site, CTA will provide full sky coverage and maximize the potential for the rarest phenomena, such as very nearby supernovae, gamma-ray bursts or gravitational wave transients. The observatory cover a huge range in photon energy, from 20 GeV to 300 TeV. This very wide energy range necessitates the use of at least three different telescope types: Large, Medium and Small-Sized Telescopes. The wider field of view and the improved sensitivity will enable CTA to survey hundreds of times faster than previous TeV telescopes [2]. The IACT works by imaging the very short flash of Cherenkov radiation generated by the interaction of relativistic charged particles with the atmosphere. The cascade only lasts a few billionths of a second. CTA's large mirrors and high-speed cameras will detect the flash of light and image the cascade generated by the gamma rays for further study of their cosmic sources. Since cascades are in the very high energy (VHE) range, the number of events detected is very low. Using more than one hundred telescopes between the northern and southern arrays, the possibility to detect them will improve significantly. The Small-Sized Telescopes (SST) start working at a couple of TeV and are expected to detect emission at tens of TeV and at highest energies, which come from extragalactic sources and from our galaxy, respectively. Since our galaxy is best observed from the southern hemisphere and the corresponding showers produce a large amount of Cherenkov light, the SSTs are ideal for the southern hemisphere array only. For low energies gamma rays Large-Sized Telescopes (LST) are required, because photon-initiated air showers produce only a small amount of Cherenkov light. LSTs and MSTs will be installed in both sites. CTA will use more than 7,000 highly-reflective mirrors to focus light into the telescopes' cameras, which convert it into data [2]. The cameras are sensitive to Cherenkov faint flashes and use extremely fast exposures to capture the light. CTA will be able to observe objects above 20 degrees elevation during dark sky conditions [2]. CTA will use both photomultiplier tubes (PMTs) and silicon photomultipliers (SiPMs) to convert the light into an electrical signal that is then digitised and transmitted [2].

2.1 CTA response functions

The instrument response functions provide a mathematical description that links the measured quantities of an event to the physical quantities of the incident photon. The instrument response functions for CTA are factorised into the effective area $A_{eff}(p,E,t)cm^2$, the point spread function $PSF(p'|p,E,t)$, and the energy dispersion $E_{disp}(E'|p,E,t)$. [?] Each response is stored in a single FITS file, which contains an additional table that describes the background rate as function of energy and position in the field of view. CTA response functions are avaiable for the northern and southern arrays, optimised for exposure times of 0.5 hours, 5 hours and 50 hours. The full energy migration matrix is provided, in each of the the IRF files, in two versions: one filled with all gamma events surviving the gamma/hadron separation cuts, suitable for cases in which there is no a priori knowledge of the true direction of incoming gamma rays (e.g. for the observation of diffuse sources), and another one filled after applying a cut on the angle between the true and the reconstructed gamma-ray direction (for observations of point-like objects) — the angular cut is the same used for the calculation of the point source sensitivity. [?]

3 Astrophysical sources of high-energy gamma rays

The only way to gain information about acceleration sites is by observing the neutral particles, as photons and neutrinos, which are not deflected by magnetic fields. High-energy photons interact with matter in three distinct processes: via the photoelectric effect, via Compton, inverse Compton and Thomson scattering processes and via the pair production process. The source association is primarily referred on close positional correspondence, while the source identification is based on period variability, relatively common in gamma-ray sources. The source spectral shape, defined as the photon flux as a function of the energy, in most cases is a simple power law $dN/dE = K(E/E_0)^{-\alpha\gamma}$. Photons are called gamma rays when their energy is $E \geq 0.5MeV$ and they have the smallest wavelengths and the most energy of any wave in the electromagnetic spectrum. They are produced by the hottest and most energetic objects in the universe, such as neutron stars and pulsars, supernova explosions, and regions around black holes.

3.1 Gamma-ray binaries

Gamma-ray binaries are a subclass of high-mass binary systems, composed of a massive star and a compact object, whose energy spectrum peaks at high energies (HE, $E > 100MeV$) and extends to very high energies (VHE, $E > 100GeV$).

The variability lightcurve and the spectral shape in the MeV domain provide information on the origin of the accelerated particles, the efficiency of the acceleration process, and the amplitude of the magnetic field. One peculiar feature of these systems is the periodicity in the signal, due to the orbital motion.

The system considered in this work, called LS I +61 303, hosts a compact object orbiting around massive young star of Be spectral type. Because of the uncertainty in the inclination of the system, the nature of the compact object remains unclear. A young pulsar was at first suggested to be responsible for the observed radio emission, but no pulsations have ever been detected [3].

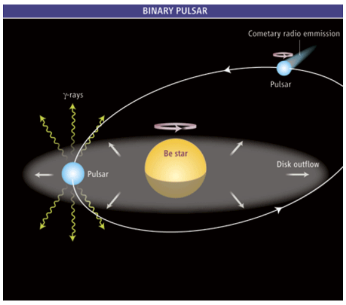

Figure 1: A binary system with a pulsar and a Be star [4].

A particular characteristic first discovered in radio and later found at VHE is the presence of two distinct periodicities, one of 26.5 days and another of 1667 days [5].
The first one is associated to the orbital period, whereas the second one has been suggested to depend on the decretion of the Be star disc. The energy spectrum presents a cut-off at GeV energies, and this might implies that the GeV and TeV gamma rays originate from different particle populations. The propose is that these populations are naturally produced by electrons accelerated on a double shock structure created within the binary system as a result of the interaction of the pulsar and massive star winds. The shock from the side of the pulsar is able to accelerate electrons to higher energies than the one from the side of massive star. These two populations of electrons produce two component γ-ray spectra caused by the IC scattering of stellar radiation [3].

4 Challenges of gamma-ray astronomy

The gamma-ray astronomy challenges of measuring light curve of gamma-ray binaries with ground-based gamma-ray observatories are due to:

- distinguish the gamma rays from the charged cosmic rays,
- the very short duration of the Cherenkov flashes,
- the small intensity of the signal,
- the very large background from the night sky and therefore the need of dark nights only,
- the very low fluxes at high energies,
- the visibility of the source throughout the year.

To detect the short flashes of light produced by cosmic rays and gamma rays as they hit the earth's atmosphere, the telescopes' cameras must be about a million times faster than a digital camera. For this reason, are required high-speed digitisation and technologies capable of recording shower images at a rate of one billion frames per second, sensitive enough to resolve single photons. Cherenkov detectors can only be operated during clear moon-less nights to obtain reliable data and the operating cycle is restricted of about 10% [6]. To optimize the observation strategy, acquisition systems should perform many short observations to detect highest energies photons or very few long observations to detect lower energies, taking into account the orbital period and the shape of the light curve. The basic idea of integrating detectors is to measure the lateral distribution of the Cherenkov light with an array of photomultipliers distributed over a large area on ground level.

4.1 Background estimation

The technique was established by the pioneering work of the WHIPPLE telescope, to suppress as much as possible hadron induced showers. The subtraction of non-γ-ray induced air showers is a major challenge. This background can be significantly reduced using image-shape selection criteria, but cannot be removed completely and it can leads to systematic errors and even produce an artificial source. the classical approach to background subtraction was the *ON/OFF tecnique*. In this mode, observations centred on the target source are interspersed with equal–length observations of an empty field at equal zenith angle, typically a region offset in Right Ascension by 30 minutes [7]. The background is assumed to be equal in the two runs, the difference between counts provides a measurement of the γ-ray signal. A major disadvantage of this approach is that only half of the available dark time is spent in the *ON mode*. To avoid this problem, the targeted source region is keeped in the field of view (FoV) at all times, with an alternating offset relative to the system's pointing direction (typically $\pm 0.5 deg$ in Declination) [7]. A background estimate (*OFF data*) for the source region (*ON data*) can then be derived from a region on the opposite side of the FoV from the same run as the *ON data*. This is the so called *Wobble mode* (see [6]), in which the pointing position of the telescope has an offset (by a certain angle, called the *wobble distance*) with respect to the position of the source under observation. Under such wobble observations, mode ON and OFF regions are observed simultaneously, what makes an efficient use of the limited duty cycles of IACTs. Given a number of counts N_{on} in a test region, and N_{off} counts in a background control region, the gamma-ray excess is defined as $N_{excess} = N_{on} - \alpha N_{off}$ [6]. There are two ways to determine the background: the *ring-background model*, in which a ring around a trial source position is used to provide a background estimate, and the *reflected-region-background model*, originally developed for wobble observations. In this latter background model, each OFF region is the same size and shape as the ON region and has equal offset to the observation position, and the ON region is reflected with respect to the FoV centre to obtain one OFF region.

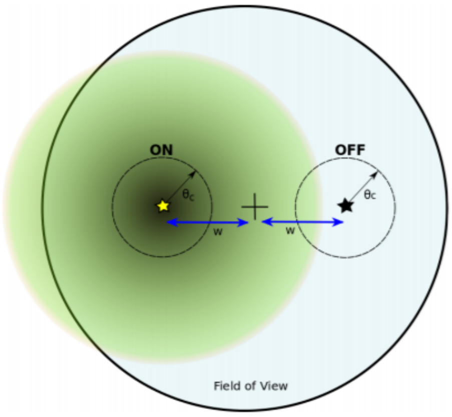

Figure 2: Schematic configuration of the FoV during wobble mode observations. The telescope pointing (black cross) has an offset distance w with respect to the center of the source. *Signal (ON)* region is defined as a circle around the center of the source, *OFF* region is defined with same angular size, symmetrically [7].

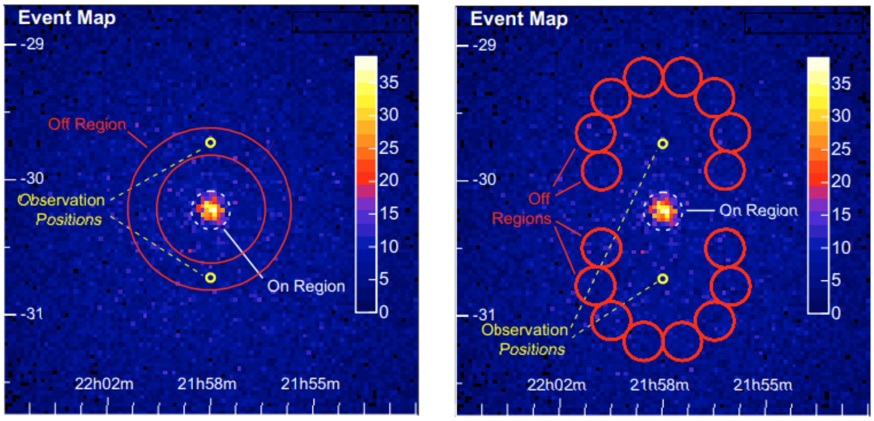

Figure 3: Schematic illustration of the *ring (left)* and *reflected-region (right)* background models. The data were taken in *wobble mode* around the target position with alternating offsets of $\pm 0.5 deg$ in declination. [8]

5 Methodology

To fulfill the project purpose, we used a Python package for gamma-ray astronomy, called *gammapy*[1], which is a prototype for the Cherenkov Telescope Array (CTA) science tools. We want to simulate and fit a light curve of a source with CTA, using the CTA 1DC response. The calculation is performed in a simulation environment, which is identified as "toy Monte Carlo", and used for further elaboration of its results.

Variable sources require time variable simulations, for instance GRBs are described by decaying light curves, since their signal decreases in time. Considering that gamma-ray binaries have a variable flux due to their periodicity, we expect that the light curve follows a periodic trend. The source of which we are simulating the light curves is LS I +61 303.

[1]https://docs.gammapy.org/0.18.2

5.1 Proposed approach

The proposed approach consists in:

- create spectral datasets within given time intervals,
- define spectral and temporal profile,
- generate a source model built up these profiles,
- perform the simulation,
- extract the light curve from the dataset,
- fit the model with the simulated light curve.

After importing some specific modules of *gammapy*, we choose the appropriate IRFs, which is for CTA North, 20 deg zenith angle and average azimuth pointing, optimised for five hours of observations. We set the center of the observations with the galactic coordinates of the source. Then, we define the reconstructed and the true energy axis, considering the TeV energy range, and the *on-region* of the observations, which are performed in the wobble mode. Note that in the wobble mode the source is not in the center of the camera, in this way we can have a symmetrical sky position from which background can be estimated.

The source model is defined, and it is a combination of spectral and temporal model, defined respectively as a power law and a periodic function. For the power law, we choose an index of 2.5 and an amplitude of $3 * 10^{-12} cm^{-2} s^{-1} TeV^{-1}$. The temporal model is generated defining a sine function, whose parameters are period, frequency, amplitude, phase and offset. The values of the *time* and the *normalization* are written into a *FITS file*, used to create the temporal model to obtain a sinusoidal light curve. My temporal model starts the 1st August 2021 (59427.0 MJD) and it takes a period of 30 days.

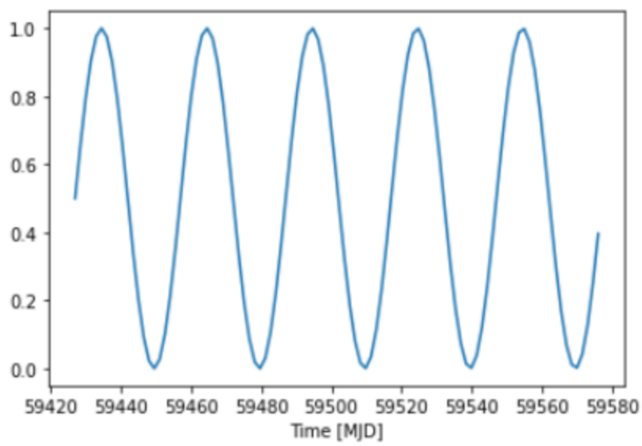

Figure 4: Plot of the sinusoidal model. Here are plotted five periods.

After combining the two models, we have created our model to perform the simulation. In the dataset, we choose 30 homogeneous observations in a time interval of 60 days, each separated from the other by two days and with a livetime of 60 minutes equal for all of them. Once create the dataset, we perform the simulation, defining firstly an empty spectrum dataset and then filling it with observations which follow the simulated model. We must be careful to make sure that the period of the model cover all the duration of observations. We obtain in this way a reduced dataset, in which we have information about background, excess photons that we believe are the number of gamma-ray like photons, significance, predicted number of counts, counts rate and so on.

To have a look to the trend of the points, we plot the *excess counts* as a function of the time. We notice that they follow a sinusoidal pattern, as we wanted. Since the order of magnitude of the flux is not so high, we also have some negative excess counts and it means that we have no detection in these specific observations.

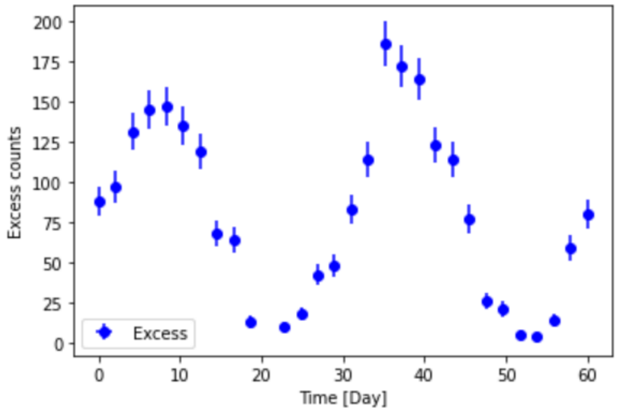

Figure 5: Data excess plotted as a function of time in days. Error bars for each point are shown.

5.2 Fitting

Our next step is to fit the light curve with our initial sine function. Here we choose guess values for frequency, amplitude, phase and offset, and with the command $curve_{fit}$ from *scipy* we fit our simulated data as a function of time. At this point, we recreate the fitted curve using the optimized parameters, and as we see from the plot, it match data so much better than the first guess.

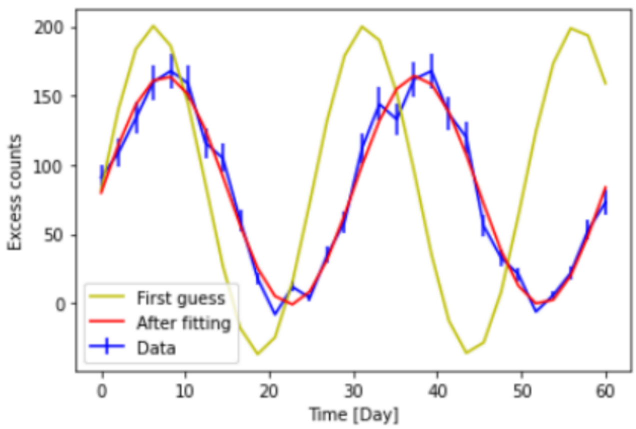

Figure 6: In this plot are shown the simulated data and the first fit with guess parameters, to compare it with the curve with optimized ones.

In the Fig. 5 we see that statistical errors are added to each point, calculated for excess counts at the first order as the square root of values. For the calculation, we have taken into account only positive excess values, excluding negative counts. Then, the error on the x-axis is half of the bin width, and since we have bin width of 60 min, the error should be equal to 30 min.

At the end, we have calculated the *chi squared* χ^2 and the *reduced chi squared* χ^2/N, by dividing the *chisquare* by degrees of freedom. Degrees of freedom are equal to $N_{exc} - N_{par}$, where N_{exc} is the number of data points having positive excess and N_{par} is the number of parameters of the sinusoidal function. The *reduced chi-squared statistic* is used to test the goodness of the fit. An ideal value is on average $\chi^2/N \sim 1$, which indicates that the fit is good and the predicted model match quite well observations. In our case, we obtained a $\chi^2/N = 2.055396$, and it means that the fit has not fully captured the data or that the error has been underestimated.

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