PROSPECTS FOR CTA OBSERVATIONS OF GAMMA-RAY EMISSION FROM GRAVITATIONAL WAVES AND GAMMA- RAY BURSTS

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Abstract

The Cherenkov Telescope Array (CTA), the next generation Imaging Array Cherenkov Telescope (IACT) , will have heightened sensitivity, larger energy range and more precision in angular and energy resolution. Since the construction of the CTA has yet to be completed, it is important to determine the prospects for CTA to follow up gravitational wave (GW) events by observing their complementary transient gamma ray bursts (GRBs). This is done using ctools, a python tool used created specifically for the CTA. With this tool, one can simulate events of known and artificial sources with the theoretical sensitivity specifications in the instrument response functions. Specifically, we used ctools to consider two of the brightest GRBs detected, the short GRB 090510 and the long GRB 130427A to try to produce and subsequently analyze the time dependent flux that follows a power law. From this relationship, the likelihood of the CTA following up GRB from GW bases on durations and signatures of the respective long or short GRB can be deduced.

1 Introduction

1.1 Gamma-Rays

The study of gamma rays as Very High Energy (VHE) in the range >100 GeV can potentially yield a plethora of scientific results and information on active galactic nuclei (AGN), pulsar wind nebulae and supernova remnants as a shortlist. Expectedly, the Cherenkov Telescope Array (CTA) will detect over one thousand gamma ray sources, approximately 10 times more than currently known to the astroparticle physics community. CTA's much improved sensitivity and angular resolution will enable the study of populations of AGN and pulsars in addition to more promising investigations into extragalactic background light (EBL), Lorentz invariance violation and more importantly into the phenomena of gamma-ray bursts (GRBs) as GW transients (See 1.4)**.** [1]

1.3 CTA

All Imaging Atmospheric Cherenkov Telescopes (IACT)'s, including the next generation ground based CTA, use VHE gamma-rays to study outer space by collecting Cherenkov light. Telescopes such as the H.E.S.S., MAGIC, and VERITAS—the predecessor of CTA—together with the Fermi-LAT (Large Area Telescope), have combined to provide lots of information about various astronomical phenomena in the universe through VHE gamma-ray detection.

The CTA aims to employ and improve the aspects of the highest performing current IACTs. The project will attempt to cover the entire sky by setting up arrays totalling over 100 telescopes in both the southern hemisphere in Chile and one in La Palmas in the Canary Islands [2].

In addition, the CTA will extend the energy range of VERITAS and sharpen the angular resolution of images by strategically arranging three different sized telescopes: the Large Size Telescope (LST) 23 m in diameter and energy range ~20 to ~200 GeV, the Medium Size Telescope (MST) 12 m in diameter and energy range ~100 GeV to ~10 TeV and finally the Small Size Telescope (SST) 4 m in diameter and energy range ~5 TeV and ~300 TeV. LSTs and MSTs will be constructed in both the northern and southern site focusing on photons closer to the low energy threshold with relatively high flux, but consequently poor Cherenkov image. The SSTs will be built exclusively in the southern hemisphere due to the visibility of the Galactic plane. [3]

Figure. 1 Image of the Prototype Schwarzschild-Couder Telescope (PSCT) from the live feed on CTA website [4]. This is a proposed design of the MST and was taken on August 1, 2017 at 10:56. [5]

1.2 The Cherenkov Technique

IACTs detect gamma-rays by imaging Cherenkov light. An incident VHE gamma-ray interacts with nuclei of earth's atmospheric molecules producing electron positron pairs moving at relativistic speeds. These high energy, relativistic particles undergo highly energetic electromagnetic radiation called Bremsstrahlung radiation during which photons produce more pair production. The subsequent air shower of particles moving relativistically produces a flash of light that reflects off of the mirror on the telescope and onto a set of photomultiplier tubes which digitize the image of the shower.

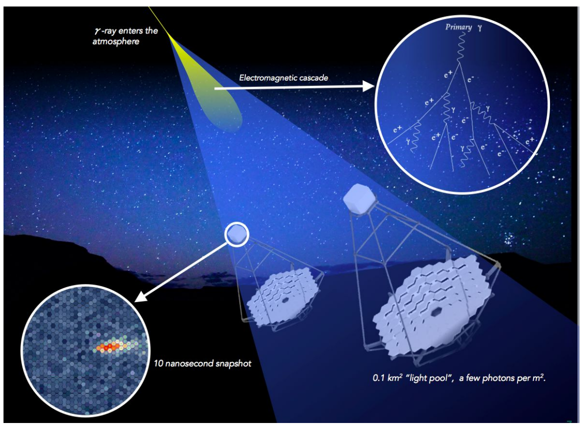


Figure. 2 Diagram of an IACT collecting photons from a Cherenkov air shower [6].

1. 4 GWs and GRBs

VHE gamma-rays can be emitted as a product of the merging of binary neutron stars, the merging of a black hole and neutron star, or the core collapse of a massive star. Particularly in the case of a binary star system, two neutron stars orbit around each other. Over time, as they rotate within the orbit, they emit GW which combined with other mechanisms results in a loss of orbital energy in the system. This causes an inspiral—a decrease in the orbital radius—causing the objects to rotate faster and emit even stronger gravitational radiation. Eventually, the neutron stars merge but some of the matter doesn't get compacted. Instead, it forms accretion disk of or rapidly spinning matter. The disk is full of ionized particles such that their magnetic field lines get and form a jet propagating perpendicularly out from the core. Since the rest frame of the jet has lower energy than our rest frame, the high energy particles can propagate out of the jet at relativistic speeds. Some of the particles in these jets are gamma rays lasting generally < 2 seconds for prompt emission although prompt gamma-ray emission can be delayed.

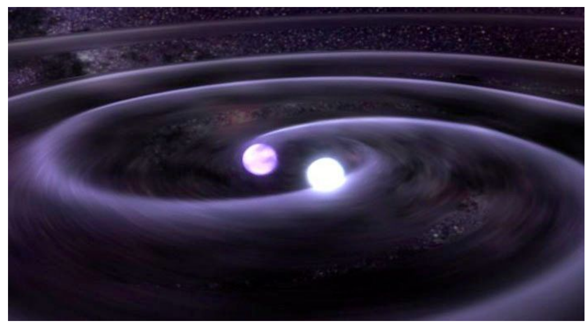


Figure 3. Artist's rendering of a binary neutron star system orbiting around each other and sending ripples of gravitational waves through space-time. [7]

Long GRBs, on the other hand, are believed to be a byproduct of the core collapse of a massive, rapidly rotating star leading to a supernova explosion and resulting in a hypernova. It's core is rotating very rapidly and at some point its shape distorts becoming aspherical which induces a quadrupole moment to the mass distribution. If the quadrupole is time dependent, then the supernova will emit GWs and GRBs. The emission from a hypernova is characterized as a long GRB which lasts from a few to several hundreds of seconds, though again the time delay between the GW signal and GRB signal is unclear.

A black hole and neutron star merger and binary black hole mergers follow essentially follows the same mechanism as stated above except the binary black hole mergers hole mergers require the presence of a gas for there to be any electromagnetic radiation.

It is useful to note that the GW detections of LIGO so far (GW150914, GW151226, GW170104) have been due to binary black holes [8]. The point at which LIGO would be able to detect GW from the binary neutron star merger is immediately before the merger, if all goes well. LIGO's sensitivity for binary neutron star mergers is roughly a redshift of ~0.05, much closer than any GRB detected by FermiLAT than the long and short GRB detected by FermiLAT. This bodes well for CTA is following up GRBs resulting from the specified GW events.

2 Method/Results

2.1 Project Overview

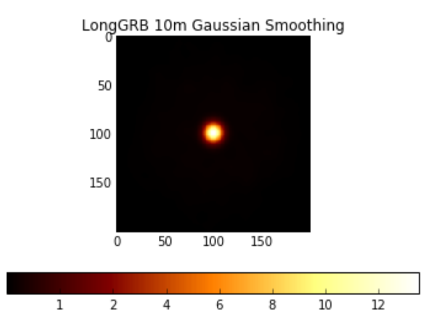
The is some inherent discrepancy between the time delays of the GW events and the ensuing GRBs that complicates CTA's follow up. This project is to study the temporal models of GRBs in order to optimize the most efficient time delays between GW events and the GRBs.

2.2 Ctools

In order to study this time discrepancy, we make use of ctools a free software created specifically for the analysis of the CTA but supports other IACTs as well. Ctools are based on the high-level astronomical gamma-ray analysis toolbox Gammalib. A Python of ctools allows control of executables while complementing the binary executables are a set of Python scripts called cscripts.

2.2 Simulations

To start, we use the tool ctobssim to simulate events with time dependent spectra. This is a type of Monte Carlo simulation as it uses a random number generator to get a statistically representative sample of the parameter space that the data might come. However, ctobssim simulates events based on the instrument response functions (IRFs) of the telescope which refer to a calibration database containing information on effective area and point spread functions. Hence, we decided to focus on simulating two of the brightest GRBs detected by Fermi-LAT—long GRB130427324 and short GRB090510016.



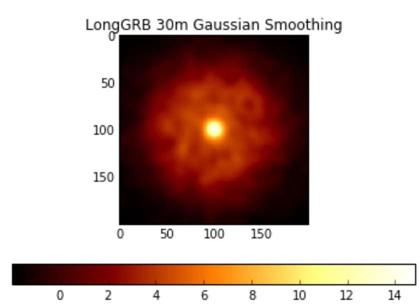


Figure 4. Reproduction of count maps of long GRB130427324 .The top figure is a 10 min. simulation starting at 1 kilosecond. The bottom is a 30 min. simulation beginning at 10 kilosecond.

We made the count maps above using `ctobssim` to generate events, then energy binned and stacked the events using `ctbin` [9]. Specifying an energy range of 50 GeV to 1 TeV and the prod2 North 0.5h irf—the older generation irf using the full telescope array in the northern hemisphere for a half hour simulation—we were able reproduce the count maps outlined in E. Bissaldi's paper "GRBRicap" using the light curve as the temporal model and spectral energy files from Thomas Gasparetto as inputs [9]. As we can see here the 30 minute simulation is much more background dominated by than the 10 minute simulation. This is because we expect in the time spectrum, there to be a spike in flux essentially immediately after the event. After that, it is expected that the spectrum falls like 1/t which accounts for steep dropoff in counts from the source Both the energy and temporal spectra of the studied in this paper follow a power law where the time and energy dependent fluxes are proportional to an a range with some specified index.

Both the energy and temporal spectra of the GRBs studied in this paper follow a power law where the time and energy dependent fluxes are proportional to an a range with some specified index.

$$\frac{dN}{dE} \propto E^{-\beta} , \quad \frac{dN}{dt} \propto t^{-\alpha}$$

The values of the indexes $\boldsymbol{\beta}$ and α were extrapolated from a Fermi-GBM (gamma-ray burst monitor) catalogue of GRBs.

Name	F_p (ph/cm^2/s $\times 10^{-5}$)	Spec.index [β]	Time index [α]	$t_p(s)$
GRB080916C	500±100	2.05±0.07	1.37 ± 0.07	6.6 ± 0.9
GRB090323	6±3	2.3±0.2	1.0 ± 0.3	40 ± 30
GRB090328	9±4	2.0±0.2	1.0 ± 0.3	40 ± 30
GRB090510	3900±600	2.05±0.07	1.8 ± 0.2	0.9 ± 0.1
GRB090902B	600±100	1.95±0.05	1.56 ± 0.06	9 ± 1
GRB090926A	700±100	2.12±0.07	1.9 ± 0.2	11 ± 2
GRB091003	8±3	2.1±0.2	1.0 ± 0.2	22 ± 9
GRB100414	70±30	2.0±0.2	1.7 ± 0.3	20 ± 10
GRB110731A	220±60	2.4±0.2	1.8 ± 0.2	4.8 ± 0.7
GRB130427A	150±30	2.2±0.2	1.35 ± 0.08	20 ± 5

Table 1. Parameters used to simulate the sample of 10 GRBs, namely the peak flux F_P, the spectral and temporal indexes β and α, and the peak–flux time t_P. Data for the first 9 GRBs are taken from table 4 of [10]**.** Data for GRB130427A are taken from [11]. [9]

For the simulation, after the time energy model inputs, the only factor left was the normalization of the whole model put together:

$$F(t_r) = k_0 \left(\frac{E}{E_0}\right)^{-\beta} \left(\frac{t_r}{t_p}\right)^{-\alpha}$$

This expression is flux as a function of the repointing time t_r, the time it would the CTA to repoint to follow up a source or phenomena from other IACTs or Fermi. Here, k_0 is the normalization factor, E_0 is the scaling factor 1 MeV set to make the ___ term dimensionless. From this information, the count maps above were made. What can be done with this information a step further than count maps. With ctlike, we can do an unbinned likelihood analysis that will give test statistics corresponding to detections significance. The threshold significance of a detection is 5σ where σ is the square root of the test statistic.

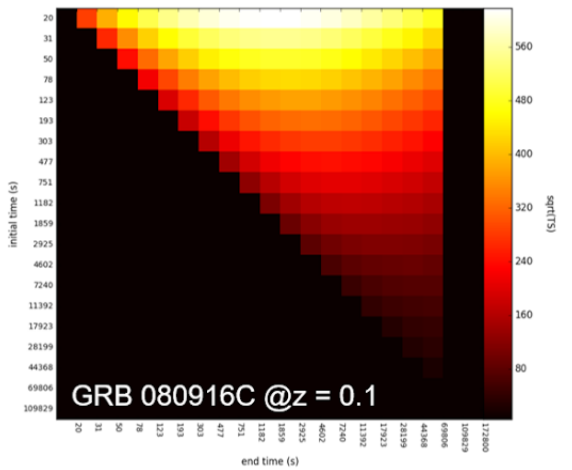


Figure 5. A 2D map of test statistic as a function of start and end time for GRB080916C placed at redshift 0.1 [9].

This map gives a sense of the timing for CTA to detect a GRB at a maximum significance as well as how that significance falls off as time progresses. The time of this plot is two days in seconds split up into fifteen logarithmically spaced bins. After each bin is simulated, it is fitted with ctlike from which the TS is extracted. As expected, with as the end time and start time increase, the signal gets dimmer and dimmer until CTA can no longer see it. The highest test statistic neither covers the full time scale as there's a hard cutoff of visibility at 65806s. Hence, there is an optimal time to observe the source. Notice that the first time bin begins at 20 seconds which corresponds to the repointing time of the LST. It begins there because of the energy the low energy range of the GRBs in FermiLAT.

FermiLAT's limitations are in it's energy resolution of the GRBs, hence, why we need to extrapolate the indexes to the CTA energy range. However, the energy of the emission is still incredibly low generally the keV-MeV range. So, we expect GRBs after GW signals to just barely meet the energy threshold of CTA, meaning that the LST will be most useful in this endeavor. It is possible that CTA will also detect VHE gamma-rays from these events. Normally, there would be an In addition, the redshift of this GRB was placed at 0.1 whereas, we expect a much brighter signal from GRBs from GW events since the redshift of thus far detected GRBs is ~0.05.

3 Conclusion/Next Steps

In order to determine the prospects for the CTA detecting GRBs falling out of astronomical events that emit GW, we used ctools in order to simulate events with spectral information obtained by FermiLAT.

The next steps for this project is continue with the outlined method and produce similar maps specifically for short GRB 090510 and long GRB 130427A. By picking two GRBs at the extremes of time durations, we can get a fuller sense of how well CTA is suited to follow up GRBs of any type coming from a wide range of GW events that LIGO will hopefully detect.

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