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Transient and multi-messenger astrophysics with the Cherenkov Telescope Array.

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Abstract

The Cherenkov Telescope Array (CTA) will be the next generation ground-based very-high-energy (VHE) gamma-ray observatory. The first of the Large Size Telescopes (LST1), is already under commissioning at Roque de los Muchachos observatory, in La Palma. The unprecedented sensitivity at short timescales of CTA will make of this observatory the leading instrument for the discovery of new transient events of both Galactic and extragalactic origin in the VHE regime. It will unveil the physics of the most extreme objects in the Universe and their interaction with the surrounding environment. The recent discoveries of the first gamma-ray bursts (GRBs) at VHE, the connection between gravitational waves and short GRBs and the association of an extragalactic neutrino with a flaring blazar, have opened new lines of research in multi-messenger and transient astrophysics. The detections of these different cosmic messengers have shown the importance of coordinated campaigns. CTA will perform follow-up observations of these events and open a new window for time-domain astrophysics at VHE. The Transient program is one of the Key Science Projects of CTA. This program includes a wide range of sources in a multi-messenger and multi-wavelength context, ranging from GRBs, to gravitational waves, energetic neutrinos, core-collapse supernovae and Galactic transients (such as microquasars, pulsar wind nebulae or novae). In this contribution, I will present the results of the exploration of the capabilities of CTA to detect new transient astrophysical phenomena at VHE.

1 Introduction

Very-high-energy (VHE, $E > 100$ GeV) transient astrophysics has proven to be a powerful tool to study extreme astrophysical processes, at the crossroads of multi-messenger and time-domain astronomy. Thanks to the development of the last generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), more than 250 sources of VHE gamma rays have been discovered, many of them of transient nature.

The Cherenkov Telescope Array (CTA) is the next-generation ground-based observatory for gamma-ray astronomy at very-high energies. It will count with two arrays located in two sites: CTA-North at Observatorio Roque de los Muchachos (ORM) in La Palma (Spain);

and CTA-South, placed near Paranal Observatory (Chile). It will count with telescopes of three different sizes (Large Size Telescopes, LSTs; Medium Size Telescopes, MSTs; Small Size Telescopes, SSTs), that will cover the energy range between 20 GeV and 300 TeV [1]. The improved sensitivity (x5-10), energy and angular resolution (by a factor 2) and energy coverage (four decades) with respect to current generation of IACTs, will make of CTA the best instrument to study the VHE gamma-ray Universe.

Specially interesting for the transient and multi-messenger case, is the unprecedent sensitivity at short timescales (see Fig. 1), which will allow for the discovery of new sources, perhaps even of new types. This short-time sensitivity is closely connected to the presence of LSTs in CTA, which allow for fast slewing (with the goal of only 20 sec to point anywhere in the sky) and low energy threshold (of only 20 GeV).

In this contribution, we summarize the work of the Transients Science Working Group (SWG) of CTA Consortium, focused on exploiting the capabilities of future CTA to discover and detect new transient sources in a multi-messenger context [2, 3], as one of nine Key Science Projects of the CTA observatory [1]. In these proceedings, we will concentrate on the topics of neutrinos, gamma-ray bursts (GRBs), gravitational waves (GWs) and Galactic transients, specifically microquasars and flares from pulsar-wind nebulae (PWNe).

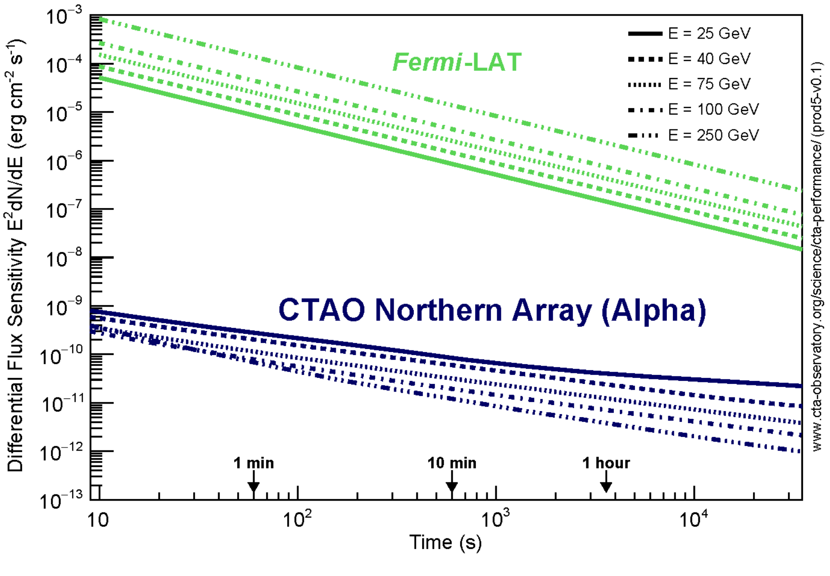

Figure 1: Differential flux sensitivity of CTAO-North as function of observation, compared to *Fermi*-LAT.

1

2 VHE transient phenomena as seen by CTA

2.1 Neutrinos

CTA will aim at the detection of the VHE counterpart of neutrino sources. Two source populations are considered: transient, based on neutrino source alerts (blazars); and steady, refereing to nu-clusters exceeding IceCube sensitivity (following the star formation rate evolution). The results of the simulations are:

- Flaring sources: the simulations consider the model of the neutrino flare of the blazar TXS 0506+056 during 2014-2015, assuming the same duration. During neutrino flares from blazars CTA will detect a counterpart for about one third of the cases after only 10 mins of observations.
- Steady sources: this scenario considers that the diffuse neutrino flux is due to steady neutrino sources. The resulting simulations show that CTA-North will be able to detect all sources down to the density of 10^{-9} Mpc^{-3} in 30 min (considering they are always visible to CTA), given that they could be observed at low to mid zenith angles (20°-40°),.

Considering these results, we can conclude that CTA will detect both flaring and steady sources of neutrino counterparts. For a more detailed overview check [5].

2.2 GRBs

The search for VHE emission from GRBs supposed a major challenge for IACTs from both the technical and the scientific point of view for more than a decade. The discovery of GRB 190114C [14] and GRB 180720B [10] finally proved that GRBs are indeed sources of VHE gamma rays. IACTs aim not only at detecting the afterglow, but also the prompt emission.

Regarding the afterglow component (prompt simulations are on-going), to test the detectability prospects and rates with CTA, the GRB task force has simulated 1000 bright GRBs detected by Swift with the population synthesis code POSyTIVE [9]. Considering visibility constraints, duty cycle, detection delays and assuming detection if 90% of trials are successful, we conclude that about 10% of the visible population will be detected by CTA, with a rate of about ∼2 detected GRB per year.

2.3 GWs

The detection of GW170817 with LIGO-Virgo [13] provided the first evidence of binary neutron star (BNS) mergers as progenitors for short GRBs (sGRBs).

Our goal is to perform follow-up of GW alerts to search for a putative VHE counterpart. For understanding the chances of CTA to detect these events, the GW task force of the Transients SWG has performed simulations of BNs mergers accompanied by sGRBs, making use of the GWCOSMoS database [18, 19]. Fig. 2, shows the percentage of detectable GRBs, both on-axis and off-axis, given an exposure time as a function of the delay from the onset [20]. We can conclude that CTA will be sensitive enough to detect more than 90% of on-axis sGRBs with time delays up to 10 min, while about 50% of off-axis GRBs will be detected within a few hours assuming the same time delay. For a more detailed information, check [20]

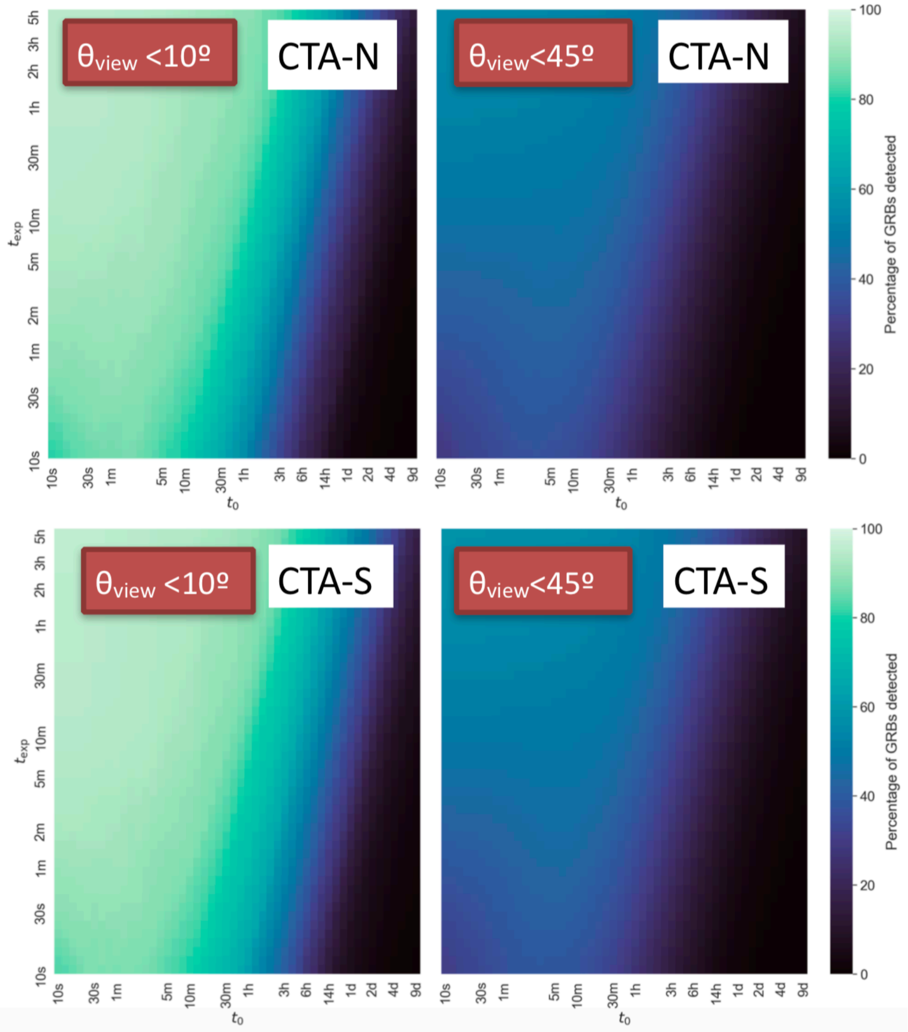

Figure 2: Percentage of detected GRBs as a funcion of the exposure time versus the time delay, both for on-axis (left) and off-axis (right) sGRBs for both CTA arrays. Figure adapted from [20].

2

2.4 Galactic transients

The topic of Galactic transients cover all those sources in the Milky Way that show unexpected flaring emission, ranging from microquasars, to novae, PWNe or magnetars, among others (see [4] and references therein). In this contribution, we focus on the chances to detect emission from two sources of interest: the microquasar Cygnus X-1 and Crab Nebula (flares). In both cases, the simulations are performed only for CTA-North array, due to visibility constraints.

- Cygnus X-1: this microquasar, composed of a massive O star and a black hole, showed a hint of transient emission at 4.9σ in an 80-min observation by [16]. Persistent emission has been reported in *Fermi*-LAT after 7.5yr of data [22]. For the CTA-North simulations in the energy range 100 GeV–1 TeV, the Galactic transients task force simulated both the transient and persistent component. For the transient emission, the MAGIC hint [16] was extrapolated. In the case of persistent emission, we used the lepto-hadronic model by [12], assuming 50 h of observations. Our results led to the detection of both transient (at 44σ) and persistent emission (39σ) from the microquasar Cyg X-1.
- Flaring emission from the Crab Nebula: the Crab Nebula is the standard candle for VHE astronomy. However, it shows flaring emission in the MeV band [21, 8] with timescales of hours. In order to discover this flares at VHE for the first time, we tested the capacity both of the full CTA-North array and a subarray of 4 LSTs, to detect flares of different intensities [17, 4]. There are good prospects for detection for CTA and especially LSTs, leading for a detection in the low energy range in < 5h.

For a more detailed analysis of the different Galactic transient cases to be studied by CTA, check [4].

3 Towards CTA

The first LST (LST1) of CTA-North was inaugurated in 2018 and it is finalizing its commissioning phase at ORM. LST1 is already producing scientific data and performing follow-up of transient events [7]. LST1 has already detected its first transient source of Galactic origin: the recurrent symbiotic nova RS Ophiuchi [6], results that are compatible with those reported by [15, 11]. The construction of the three remaining LSTs has already started and its finalization is planned for end of 2025. The first step to discover new transient sources with unprecedented sensitivity with the future CTA observatory is already taken.

Acknowledgments

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of ctools, a community-developed analysis package for Imaging Air Cherenkov Telescope data based on GammaLib, a community-developed toolbox for the scientific analysis of astronomical gamma-ray data; and gammapy, a community-developed core Python package for TeV gamma-ray astronomy.

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