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Transient TeV Astronomy with Cherenkov telescopes in the Canary Islands

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Abstract

The past decade represented the kick-off and settlement on multi-messenger and time-domain astronomy, coincident with the blooming of transient TeV astronomy. Over the past decade, new sources of very-high-energy (VHE) gamma rays have been discovered, opening new physics in this energy regime: the discovery of a TeV counterpart of long gamma-ray bursts (GRBs) via the detection of afterglow emission, the association of a neutrino with a flaring blazar or the VHE signal of hadronic origin from a nova. Many of these new VHE transient sources have been discovered with Cherenkov telescopes located at the Roque de los Muchachos (ORM) in the Canary Island of La Palma, one of the only three observatories hosting this type of instrumentation in the world. In this contribution, we review the TeV sources of transient nature that have been identified in the VHE regime in a multi-messenger context, making use of the MAGIC telescopes and the first Larged-Size Telescope (LST-1), and we briefly outlook for new perspectives with the future Cherenkov Telescope Array Observatory (CTAO), whose northern array will be located at ORM.

1 Introduction

The birth of the Imaging Air Cherenkov Technique (IACT) led to the detection of very-high-energy (VHE; E>100 GeV) gamma rays for the first time. Currently, over 300 VHE sources have been discovered[1] with ground-based experiments. The Canary Islands host one of the three locations worldwide where IACT experiments have been operational for over two decades. Located at Observatorio Roque de los Muchachos (ORM), the MAGIC telescopes have detected about ∼80 sources of VHE emission and have played a key role in revealing new sources of transient nature in the TeV regime, key for time-domain and multi-messenger astronomy (see i.e. [1] for a review on transient TeV astrophysics).

The northern array of Cherenkov Telescope Array Obvervatory (CTAO), the first open ground-based VHE observatory, CTAO-North, will be based at ORM [2], and it will be

[1] `http://tevcat.uchicago.edu/`

composed of four Large-Sized Telescopes (LSTs) of 23-m diameter and nine Medium-Sized Telescopes of 12-m diameter. The prototype of the LSTs, LST-1, is operational since 2018 [3] and the three additional LSTs are currently being installed. By 2026, ORM will have the most sensitive IACT array worldwide. Additionally, the Observatorio del Teide (OT), in the island of Tenerife, will be hosting the ASTRI Mini-Array, an array of 9 IACTs of 4.1-m diameter that will cover the higher end of the VHE spectrum [4]. The first telescope is already installed.

Considering the existing and future instrumentation, the Canary Islands will become the most important observatory for ground-based gamma-ray astronomy in the imminent future. In this contribution, we briefly review the discoveries performed by the current IACTs MAGIC and LST-1 to TeV transient astrophysics. We also review the future prospects for detection of VHE sources with the future CTAO and ASTRI mini-arrays.

2 Novae

Novae eruptions are sudden increases in the brightness of a binary system composed by a white dwarf (WD) that accretes material from a companion star. The increase in brightness is caused by the thermonuclear runaway produced due to the accumulation of material onto the surface of the WD. Depending of the type of the companion star, novae are classified into classical (main sequence star) and symbiotic (red giant). While symbiotic novae have shown recurrent eruptions (within human timescales), classical novae do not (or have longer recurrency periods).

Both classical and symbiotic novae were identified as high-energy (HE; E>100 MeV) sources by *Fermi*-LAT over a decade ago [5, 6]. The spectral energy distribution (SED) was however measured up to few GeV and the nature of the HE emission was not confirmed. The question whether novae could be VHE emitters was unanswered for almost two decades, until the eruption of the symbiotic recurrent nova RS Ophiuchi (RS Oph) in 2021. In the northern hemisphere, the VHE signal was detected by MAGIC [7] and LST-1 telescopes [8], with detections from the H.E.S.S. telescopes in the South [9]. The MAGIC and LST-1 emission was significant during the first four days after the outburst, coincident with the optical and HE peaks. The gamma-ray emission is best fit with a hadronic scenario, probing the acceleration of protons in novae shocks. The contribution of these protons to the overall cosmic ray sea is limited, but novae do enhance the local cosmic-ray density, creating bubbles of up to $\sim$10 pc in the case of recurrent novae [7].

3 Gamma-ray bursts

The MAGIC telescopes were designed to perform a fast repositioning in order to obtain a prompt reaction to transient signals, GRBs specifically. After almost two decades of software and hardware improvements, the first long GRB in the VHE regime was discovered: GRB 190114C [10, 11]. The VHE signal was detected from T0+50 sec for over 20 minutes. The afterglow emission observed by MAGIC was proposed to originate from a second component via synchrotron self Compton (SSC). Since then, a total of five long GRBs have been reported at TeV energies (see i.e. [12] for a review). MAGIC also counts with the record of the most distant VHE source, GRB 201216C located at z=1.1 [13]. The SSC scenario can explain the broadband emission from optical up to VHE.

Regarding short GRBs, a 3.1σ signal hint at E>0.5 TeV has been reported by MAGIC on GRB 160821B at z=0.162 [14]. The MAGIC observations started 24 sec after the burst trigger and lasted 4 hours. Optical-infrared observations revealed a kilonova associated to this GRB [15, 16]. This is the only hint of emission associated to this kind of transient up to now.

4 Neutrino-blazar connection

The first association between a high-energy neutrino and an extragalactic flaring source, happened in September 22, 2017, when a neutrino (IC170922A) with an energy of 290 TeV was found to be positionally coincident with the flaring blazar TXS 0506+056 [17]. HE gamma-ray emission was reported by *Fermi*-LAT and AGILE. The VHE signal was discovered by MAGIC on September 28, reaching energies of up to 400 GeV. A 3σ correlation of the neutrino with the flare of TXS 0506+056 was reported. The detection of VHE emission and a coincident neutrino indicate that blazar jets can accelerate protons up to several PeV, meaning that blazars can be the birthplaces of ultra-high-energy cosmic rays.

5 Future prospects

CTAO will count with unprecedented sensitivity at short-timescales, enhanced energy range and improved angular and energy resolution, making it the best future instrumentation for transient TeV astronomy. The *Transients Key Science Program* [2] focuses on the capabilities of the future CTAO to discover and detect new transient sources in a multi-messenger context, specifically on the topics of GRBs, GWs, neutrinos, core-collapse supernovae and Galactic transients. CTAO will likely discover many new sources and possibly even of new types of VHE emitters such as GW counterparts [18] or microquasars in outburst[19] among others. For a review of the Transients science program for CTAO, see i.e. [2, 20, 21, 22].

Regarding ASTRI Mini-Array, even if its core science program is not focused on transient sources, the follow-up of transient events such as GRBs and GWs will be possible (see i.e. [23, 24, 25]). As a first example, it could potentially detect nearby GRBs at z<0.5 above $\sim$1 TeV [24].

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