Astro2020 Science White Paper

Multi-messenger and transient astrophysics with very-high-energy gamma rays

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☒ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☒ Multi-Messenger Astronomy and Astrophysics

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On behalf of the CTA Consortium
https://www.cta-observatory.org/about/cta-consortium/

Abstract: The discoveries of high-energy astrophysical neutrinos and of gravitational waves in the past decade have revolutionized astrophysics. These new tools have begun to answer some of the most important and longest standing questions in astrophysics, and have also unveiled a slew of new mysteries. The rise of these new messengers is closely connected with the rise of time-domain astronomy across the electromagnetic spectrum. Gamma rays have already provided the first electromagnetic counterpart of a gravitational wave signal as well as the first evidence for an individual high-energy neutrino source. With planned instrumentation upgrades and improvements in analysis and computation techniques, the rate of such discoveries will continue to grow over the next few years. We describe the prospects for gamma-ray telescopes, particularly in the energy range greater than 20 GeV, for multi-messenger and transient astrophysics in the decade ahead. Much of the material is drawn from *Science with the Cherenkov Telescope Array* [1], a recently published book that provides a comprehensive description of the scientific prospects for CTA. We request that authors wishing to cite results contained in this white paper cite the original work.

Introduction

Since the discovery of high-energy astrophysical neutrinos in 2013 [2] and of gravitational waves in 2015 [3], there are new messengers available to complement the full electromagnetic (EM) spectrum for astronomy and astrophysics. Together these messengers have made several breakthrough discoveries, and the pace of such discoveries will accelerate over the coming decade. The study of individual astrophysical sources with these messengers began in earnest in 2017, with the first evidence for electromagnetic counterparts of both gravitational waves and high-energy neutrinos. In both cases, the first electromagnetic counterpart to be identified, and to point the way for further observations, was in the gamma-ray band.

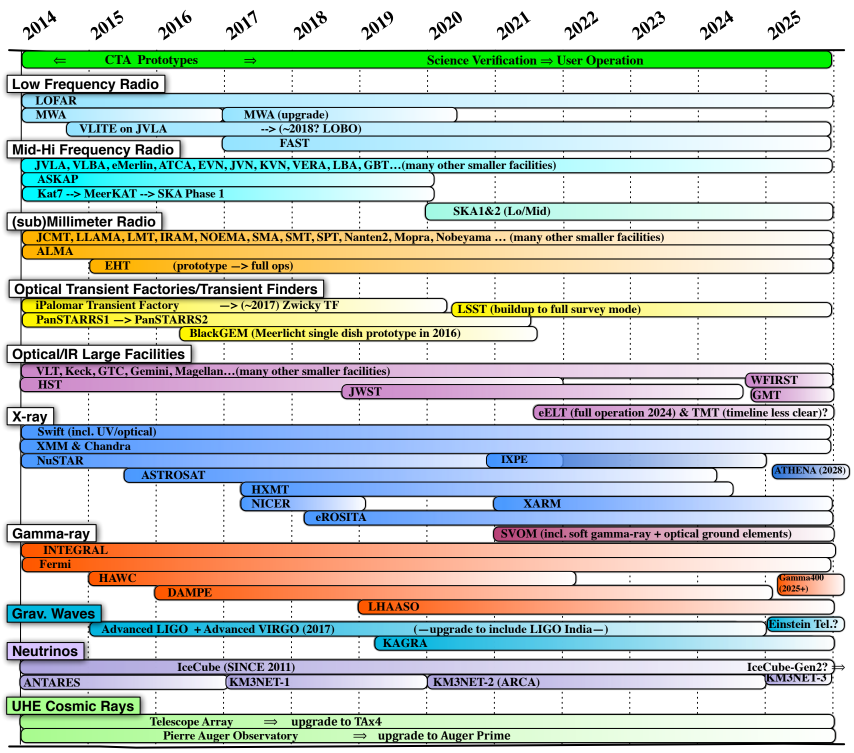

Fig. 1: Timeline of major multi-wavelength/multi-messenger facilities [1]. Note that the lifetimes of many facilities are uncertain, contingent on performance and funding. We indicate this uncertainty with color gradients.

GW170817, the first binary neutron star merger detected in gravitational waves, was observed in connection with a short gamma-ray burst detected by the Gamma-ray Burst Monitor (GBM) onboard NASA's *Fermi* Gamma-ray Space Telescope [4]. A few weeks later, IceCube-170922A, a high-energy neutrino, was detected and gamma-ray observations by both *Fermi* and MAGIC were used to identify a likely counterpart, the blazar TXS 0506+056 [5, 6]. These multi-messenger observations are beginning to answer some of the leading questions in astronomy and astrophysics, including the origins of the heavy elements and the sources of cosmic rays.

A third recent discovery emphasizes the potential for very-high-energy gamma-ray observations of astrophysical transients: MAGIC recently reported the first detection of a gamma-ray burst by a ground-based gamma-ray telescope, GRB 190114C, detected above 300 GeV with statistical significance greater than 20 σ [7].

In this white paper we focus on the capabilities of very-high-energy gamma rays for follow-up observations of astrophysical signals measured in other wavebands and messengers, as well as the potential for serendipitous discoveries. For this purpose we define "very-high-energy" (VHE) to be those gamma rays detectable with large effective area by ground-based gamma-ray telescopes, corresponding to an energy threshold of ~20 GeV. There are three techniques available for gamma-ray astronomy in this band: (1) imaging atmospheric Cherenkov telescopes (IACTs) such as H.E.S.S. [8], MAGIC [9], VERITAS [10], and CTA [1], which achieve excellent sensitivity and low (~20 GeV) energy threshold over an instantaneous field of view up to eight degrees in diameter; (2) space-based satellites such as the *Fermi* Large Area Telescope (LAT) [11], which view a large fraction of the sky but with limited effective area for the small fluxes available in the VHE band; and (3) direct air shower detectors such as HAWC [12] and LHAASO [13] in the northern hemisphere, and the proposed ALPACA [14], ALTO [15], LATTES [16] and SGSO [17] detectors in the southern hemisphere, which have excellent duty cycle and field of view but worse sensitivity, higher energy threshold, and less ability to distinguish gamma rays from background cosmic-ray nuclei. We focus in particular on the capabilities enabled by the IACT technique with large instantaneous sensitivity, while noting the complementarity of the three approaches.

High-energy neutrinos

IceCube has measured the diffuse astrophysical neutrino spectrum between several TeV and several PeV [2]. The same hadronic interactions of cosmic rays that likely produce these VHE neutrinos also produce VHE gamma rays due to the decay of neutral pions. Therefore, VHE gamma rays are a natural band to search for EM neutrino counterparts. In fact, the simplest production mechanisms for astrophysical neutrinos (involving proton-proton or proton-photon interactions) produce a gamma-ray spectrum at the source that has a spectral shape and normalization very similar to the neutrino spectrum. Unlike neutrinos, however, gamma rays can be absorbed or down-scattered during escape from their source region and/or during propagation across extragalactic space due to the effect of the extragalactic background light ([18, 19]). This difference in behavior makes the combination of complementary neutrino and gamma-ray observations powerful: detection or non-detection of a VHE gamma-ray signal from the directions of high-energy neutrinos provides diagnostic information about the distances and/or local environments of the neutrino sources.

Although TXS 0506+056 was identified as the first likely source of high-energy astrophysical neutrinos, it contributes $\lesssim$1% of the astrophysical neutrino flux measured by IceCube. Stacking studies have shown that *Fermi*-LAT-detected AGN (including blazars) can produce at most ~27% of the neutrino flux [20]. Therefore, one or more additional source class, such as star-forming galaxies [21] or radio galaxies [22] must contribute to the neutrino flux.

While the astrophysical neutrino signal has been measured statistically above atmospheric backgrounds between several TeV and several PeV, individual neutrino events can be distinguished from background only at the higher end of the range: the signal to background ratio is above unity for neutrino energies greater than ~100 TeV. The highest energy neutrinos are therefore the best candidates for electromagnetic follow-up. The direction of many of these neutrinos, specifically those that produce long muon tracks within neutrino detectors, is measured to within 1°, well matched to the several-degrees field of view of IACTs. A recent summary of results from the follow up of neutrino events by current-generation IACTs is presented in [23].

VHE gamma rays are particularly important for studies of Galactic neutrinos. While the bulk of the measured neutrino flux is likely extragalactic, there are guaranteed Galactic components due to both diffuse processes (guaranteed by our knowledge that cosmic rays collide with the interstellar medium) and individual sources (guaranteed by our knowledge that Galactic cosmic-ray sources exist). A deep and high-resolution survey measuring the VHE gamma ray spectrum throughout the Galactic plane would provide essential input for identifying Galactic neutrino sources. Once Galactic neutrino sources are identified, they are immediately known to be cosmic-ray sources, without the challenges present in disentangling hadronic and leptonic components of gamma-ray spectra. Unlike extragalactic VHE gamma rays, Galactic gamma rays below the PeV scale to not suffer from absorption on extragalactic background light (the gamma-rays can be reprocessed within local source environments of sufficient target density in matter or radiation fields).

Gamma-ray bursts and gravitational wave sources

Gamma-ray bursts (GRBs) [24, 25], the most luminous events in the Universe, are transient sources of high-energy radiation characterized by the emission of 10^{49} - 10^{54} ergs of isotropic-equivalent EM energy over a short time window ($\sim 0.01 - 1000$ s). This *prompt* emission, dominated by photons in the hard X-ray to MeV range, is followed by an *afterglow* phase detectable across the EM spectrum. Observations of GRBs have identified two main event classes, characterized by their emission time scales T: *short* GRBs (SGRB) with harder spectra and $T \lesssim 2$s, and *long* GRBs (LGRB) with $T \gtrsim 2$s and softer spectra. These two classes are expected to be associated with different source progenitors: high-mass star collapses in the case of LGRBs, and compact object mergers in the case of SGRBs. The connection between SGRBs and compact object mergers was recently confirmed by the detection of gravitational waves from a neutron star merger in coincidence with the short GRB 170817A [26].

Much remains unknown about these powerful objects, including the nature of the central engine, the properties of the GRB medium, the development and structure of the jet, and the particle acceleration processes that lead to the prompt and afterglow signals. Sensitive observations at high energies can help answer these questions. Because GRBs are detected over cosmological distances, the study of their high-energy emission also enables unique probes of fundamental physics and the properties of the extragalactic medium (e.g. [27, 28, 29]).

Above a few GeV, more than 140 GRBs have been detected by the *Fermi*-LAT instrument as of 2018 [30], and their GeV spectra are mostly consistent with extrapolations of the MeV spectrum to higher energies with no apparent cut offs. The limited statistics provided by the LAT due to its m^2-scale effective area has largely prevented the study of GRBs in the VHE range. Current generation ground-based instruments such as H.E.S.S., MAGIC and VERITAS (with typical effective areas in the 10^5 m^2 range) have active GRB follow-up programs to search for VHE emission (e.g. [31, 32, 33]). These campaigns were recently rewarded with the detection of the long GRB 190114C above 300 GeV by MAGIC [34], the first GRB detection in the VHE band.

The main challenges for the detection of GRBs in the VHE range are the short response times required to repoint a telescope to observe a GRB, their large localization errors (up to tens of degrees in radius depending on the triggering instrument) and the softening of the spectrum expected at high energies induced by EBL absorption. Current wide-field VHE instruments such as HAWC can provide near-realtime coverage for visible bursts, but typically at energies above 1 TeV [35] and with instantaneous point source sensitivity inferior to IACTs. Efforts to reduce the energy threshold of such instruments and increase their sky coverage are currently underway [14, 15, 16, 17]. The most sensitive instrument for VHE follow ups of GRBs in the coming decade will be the Cherenkov Telescope Array (CTA), with telescopes that are optimized for fast slewing (goal of 20 s, minimum requirement of 50 s) and a low energy threshold (20 GeV). These capabilities will enable the observation of VHE emission from GRBs even for high-z bursts, as illustrated in Fig. 2.

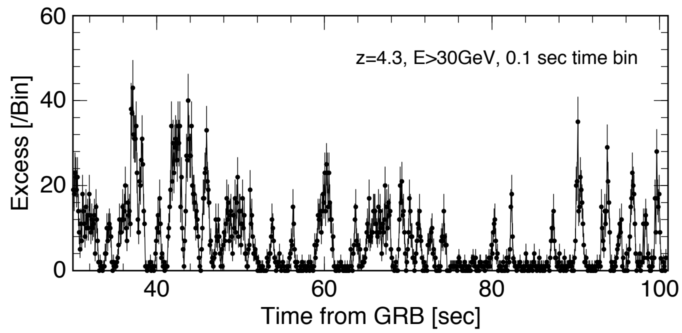

Fig. 2: Simulated CTA light curve of GRB 080916C at z=4.3, for observed photon energies above 30 GeV with 0.1 sec time binning and plotted starting 30 seconds after burst onset. For more details, see [1].

The discovery of gravitational waves from the merger of a binary black hole (BBH) system [3], and the later detection of gravitational waves from a binary neutron star (BNS) [26] that produced a short gamma-ray burst and a kilonova [4] have opened a new channel for discoveries regarding gamma-ray bursts and compact binary mergers in general. Current-generation instruments such as H.E.S.S., MAGIC, VERITAS, and HAWC are searching for VHE counterparts of the gravitational wave events detected by advanced LIGO and Virgo [36]. Wide-field instruments such as HAWC benefit from a large instantaneous sky coverage at the expense of sensitivity, while current IACTs use their $3° - 5°$ FoV to tile the $\mathcal{O}$(10-1000) deg^2 localization uncertainty regions from GW detectors [37, 38, 39]. It is expected that by 2023 the advanced LIGO and Virgo detectors will reach their design sensitivities, and that the KAGRA detector will be operational, which will result in 11-180 BNS merger detections per year [40]. Alerts from these GW detections will trigger rapid followup by CTA, which will provide the most sensitive observations in the VHE band [41].

Additional electromagnetic transients

Across the electromagnetic spectrum, a new generation of wide-field, high-time-resolution instruments will operate in the next decade, as summarized in Fig. 1. These instruments range from the Square Kilometer Array (SKA) [42] in the radio band to the Large Synoptic Survey Telescope (LSST) [43] in the optical band. They will act as “transient factories”, churning out new detections of fleeting astrophysical sources and likely uncovering entirely new classes of sources. Their predecessors and technological pathfinders are already ramping up the rate of discovery of transients including supernovae, tidal disruption events, and fast radio bursts. Each of these transient source classes may act as cosmic ray accelerators and VHE sources (for supernovae, for example, see [44, 45]).

These instruments will provide a flood of real-time, automated alerts. A VHE gamma-ray instrument capable of slewing a large effective area quickly (in less than one minute) will be capable of catching a prompt counterpart of these transients identified in other bands. Other observational strategies can yield additional discoveries: (1) A leap forward in effective area and field of view will make it possible to identify new VHE transients serendipitously and report them in real time to other observers; (2) for short-duration but high-rate classes of transients including fast radio bursts [46, 47, 48], a VHE observatory can "shadow" another observatory, pointing in the same direction at the same time in search of such transients.

Novae, one of the longest known classes of astrophysical transients, have provided some of the most exciting surprises among modern observations. The *Fermi*-LAT has shown that both classical and symbiotic novae can accelerate particles to the GeV scale [49], which had not even been considered a theoretical possibility prior to the surprise discovery. It is possible that all novae are particle accelerators and gamma-ray sources. Correlation between the gamma-ray and optical light curves indicates that the same physics powering the particle acceleration may also be responsible for most of their total bolometric luminosity. Based on these observations, novae could be a source of Galactic cosmic rays, and may even explain the spectral break in cosmic rays observed at ~200 GeV [50, 51, 52]. While the *Fermi*-LAT has revolutionized our understanding of novae, it has been unable to measure their spectra above ~10 GeV. To understand novae as particle accelerators, their gamma-ray spectra must be understood in this VHE range [53, 54, 55].

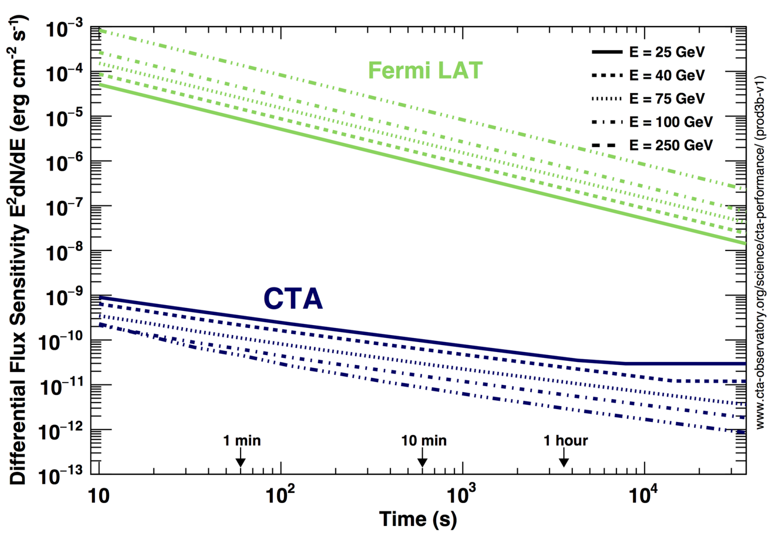

Fig. 3: Point-source sensitivity vs. observation duration for CTA compared to the *Fermi*-LAT. For short-duration transients, CTA's much larger effective area enables much better sensitivity [56].

Conclusion

The space-based and direct air shower techniques can each integrate large exposures in the VHE band over long time intervals thanks to their high duty cycle, which makes them particularly well suited for steady sources. For transient and variable (including multi-messenger) sources, the IACT technique is especially powerful, as illustrated in Fig. 3, thanks to its large instantaneous effective area and excellent background rejection capability.

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