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Nuclear and Particle Physics Proceedings 306–308 (2019) 69–73

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Strategies for the Follow-up of Gravitational Wave Transients at Very High-Energy Gamma Rays with the Cherenkov Telescope Array

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Abstract

With the observation of the first electromagnetic counterpart of Gravitational Wave (GW) transient GW170817, the potential of multimessenger astronomy has been clearly demonstrated. In its full configuration, the Cherenkov Telescope Array (CTA) observatory will be capable of rapidly covering the regions localized by future GW observations with sufficient sensitivity at very high-energy gamma rays. In view of the forthcoming deployment of its first telescopes, we identify some general strategies for GW follow-up that will improve the CTA contribution to multimessenger discoveries.

Keywords: Cherenkov telescopes, Cherenkov Telescope Array, gravitational waves

1. Introduction

The Advanced LIGO first two observing runs saw an extensive effort to search for multimessenger emission from gravitational wave (GW) sources, covering both the electromagnetic and neutrino spectra. This effort culminated, on 2017 August 17, with the observation across the electromagnetic spectrum of a gamma-ray burst (GRB) and a kilonova as a consequence of a binary neutron star merger which was detected in GWs [1, 2, 3]. The Advanced Virgo interferometer was also operational at this time and aided the discovery, reducing the sky localization region. The success of the observational campaign for this event, which marked the start of multimessenger astronomy with GWs, shows the importance of coordinated follow-up observations and of the strategies to carry them out. In the next few years, the LIGO and Virgo detectors will continuously improve their sensitivity [4], while additional GW interferometers (KAGRA, LIGO-India) are envisaged to come online, promising the regular detection of a variety of sources with potential multimessenger signatures.

The Cherenkov Telescope Array (CTA) will soon expand the multimessenger observational horizon with an unprecedented sensitivity to sources producing very high-energy (> 10 GeV) gamma-ray emission. The first CTA telescopes are envisaged to come online in 2019, bringing the first joint GW/CTA searches during the LIGO/Virgo third observing period. CTA will continuously increase its sensitivity as more telescopes are installed, broadening its reach in parallel with increased

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https://doi.org/10.1016/j.nuclphysbps.2019.07.010

GW capabilities.

It is currently unclear which is the highest gamma-ray energy that can be emitted by multimessenger sources of interest such as GRBs. The Large Area Telescope on the Fermi satellite (Fermi-LAT) has detected GRB gamma rays up to tens of GeV energies, with no clear cutoff, and with the limitation that the universe becomes opaque at the highest energies for sources at typical GRB distances. Ground-based, imaging atmospheric Cherenkov telescopes (IACTs) so far did not detect emission from GRBs, but this is consistent with the extrapolated high-energy flux from Fermi-LAT observations. Nonetheless, the observed ultra-high energy cosmic-ray flux and cosmic neutrinos show that, in general, particle acceleration and high-energy emission reach much higher energies than the current observational limit for GRBs.

Joint LIGO/Virgo+CTA observations represent a promising probe to very high-energy gamma-ray emission from extreme cosmic transients. GW detections can unambiguously identify nearby black-hole formation or evolution, and allow CTA to carry out searches that can connect very high-energy emission to the progenitor. While typical transient observations, such as those of GRBs, are at cosmological distances that hinder the detection prospects of very high-energy photons due to photon-photon absorption induced by interactions with the extragalactic background light (EBL), observed GW sources will mostly be within the distance range ($\lesssim$ 1 Gpc) at which the highest energy photons can reach the Earth. While very high-energy emission from sources of interest is uncertain, extrapolating observed GRB emission to higher energies indicates that CTA could easily detect energetic photons from GW sources [5]. Furthermore, CTA is well suited to carry out follow-up observations of GW triggers due to its fast response, large field of view and unprecedented sensitivity, enhancing the utility of joint LIGO/Virgo+CTA observation campaigns.

This contribution aims to summarize the status, operations and prospects of GW detectors and CTA, and outline the steps needed to carry out effective multimessenger surveys, giving recommendations to optimize this effort, before the start of joint GW/CTA observations. More details and discussions are given in [6].

2. Sources of Gravitational Waves and High-Energy Gamma-Ray Emission

Short GRBs are thought to be powered by neutron star - neutron star (NS-NS) or neutron star - black hole (NS-BH) mergers. The unambiguous association of GRB170817A with GW170817 recently confirmed this hypothesis at least for some short GRBs, however with a soft prompt emission extending only to ~1 MeV [3], while at very high energies the H.E.S.S. IACTs set some upper limits at later times [7]. Fermi-LAT has detected emission above 100 MeV from several short GRBs, most notably GRB090510 [8]. A time delay may be possible between a GW trigger and any short GRB emission in the case of a NS-NS merger, if the merger yields a supramassive NS; in this case the GRB may be delayed by $O(10^3\,\mathrm{s})$ with respect to the GW trigger [9, 10], which will need to be taken into consideration in designing the electromagnetic follow-up strategy. An estimate of the rate of detections by CTA of short GRBs associated with GWs gives ~ 0.03 yr^{-1} [5]; however, considering off-axis events like the recent GRB170817A, this rate should increase [3, 11]. A higher rate $0.08 - 0.5/yr$ is predicted in [12].

Some long GRBs are associated with the core collapse of massive stars. If the collapse is asymmetric enough to produce a detectable GW emission, its signal should precede the burst [13, 14].

The Gamma-ray Burst Monitor (GBM) on the Fermi satellite detected a weak transient above 50 keV, 0.4 s after the event GW150914, with a false-alarm probability of 2.9σ [15].

A refined analysis of the data of the MiniCALorimeter (MCAL) on the AGILE satellite, operating in the energy band 0.4-100 MeV, found a weak event lasting about 32 ms and occurring 0.46 s before GW170104, with a post-trial significance of $2.4\text{-}2.7\sigma$ [16], which was also produced by the coalescence of a Binary Black Hole (BBH). The characteristics of this event are similar to those of the weak precursor of short GRB090510, also in its timing, being detected about 0.46 s before its brightest emission by both AGILE-MCAL and Fermi-GBM [17, 18]. If this association is confirmed by different space instruments, it would prove that a BBH coalescence may be preceded by electromagnetic emission.

3. Sensitivity of Gravitational-Wave Detectors in the CTA Era

In 2019, we expect Advanced LIGO and Virgo to start taking data in their observing run, O3, at almost their design sensitivities, with sensitive ranges to binary neutron stars between 120-170 Mpc and 65-85 Mpc respectively. By the end of the decade and beyond, advanced detectors will reach their design sensitivities, with ranges to Binary Neutron Star (BNS) systems of $\sim$ 190 Mpc and $\sim$ 125 Mpc in Advanced LIGO and Virgo, respectively [4]. Here, we defined range as the volume and orientation-averaged distance at which the source can be detected.

About 10-20% of detected BNS events will have sky localization with uncertainties of 20 deg^2 or less during O3 when a three-detector network consisting of the LIGO and Virgo interferometers will be in operation. When LIGO India will be added to the network [19], this value will reach ~50%.

The Japanese KAGRA detector is being constructed underground near the Kamioka mines to reduce seismic noise [20, 21]. It may join LIGO and Virgo during O3, however its sensitivity may not be sufficent for a scientific contribution.

Based on current rate estimates, the expected detection rate of BBH mergers during the O3 science run in 2019–2020 ranges from a few per month to a few per week. At design sensitivity, $\approx 10^2$ BBH detections per year are expected. From the detection of GW170817, the expected BNS rate is up to one per month during O3, and may reach a few per month at design sensitivity. There is still a lack of Neutron Star - Black Hole (NSBH) merger detections, however the first one may happen during O3. Finally, we should be ready for a nearby Core-Collapse SuperNova (CCSN) during O3.

4. Importance of Low-Latency Follow-Up

The utility of GWs in studying astrophysical processes is greatly increased by the simultaneous observation of electromagnetic and/or neutrino emission from the same sources. Consequently, there is a significant effort to enable Earth-based GW detectors to rapidly identify and localize GW source candidates, and share this information with partner observatories. GW candidates were rapidly shared with a large number of partner observatories already during the operation of Initial LIGO/Virgo, which was further expanded during LIGO first observing run (O1) and then improved during LIGO/Virgo second observing run (O2).

Going forward, GW candidates will be shared at increasing rates and decreasing latency. The False Alarm Rate (FAR) of shared triggers was set at 1/month during the O2 observing run. The future trigger rate will likely be higher than this. Thanks to the Open Public Alerts given during O3, follow-up observatories can select GW triggers based on different parameters: the arrival time, reconstructed progenitor type, source distance, direction, significance (FAR). For compact binary mergers, information on the possible disruption of a neutron star will be also given, pointing out electromagnetically bright sources.

GW candidates can be identified with a latency of ~ 1 min. Following this initial detection, during O1 and O2 a human data quality check introduced a ~ 30 min delay. Given the expected short duration of very high-energy emission, CTA will need to rely on the earliest available reconstruction. A later human data quality check may result in a retraction of the GW candidate.

5. CTA Telescopes

The CTA observatory is being designed by an international consortium, which is currently building prototypes and characterizing them.[1] To provide all-sky access, CTA will comprise two arrays, with one deployed in the Northern hemisphere, on La Palma (Spain), while Paranal (Chile) is the site in the Southern hemisphere. Meeting the ambitious CTA design goals, including an overall increase in sensitivity of about an order of magnitude compared with the current generation of IACTs [22], requires a large number of telescopes of different sizes in order to cover the energy range from 20 GeV up to above 100 TeV. The telescopes are grouped in three sizes; large-sized (23 m diameter LSTs), medium-sized (12 m MSTs) and small-sized (4 m SSTs). A prototype of a dual-mirror version of the MST (Schwarzschild-Couder Telescope (SCT) with a 9.7-m primary mirror) is also being built. The LSTs provide access to the low-energy range (≤ 0.1 TeV), the SSTs to the high-energy range (≥ 10 TeV) while the MSTs ensure enhanced sensitivity in the core energy range of CTA (0.1 – 10 TeV). The telescopes will be arranged on the ground such that the LSTs are grouped together, surrounded by an array of MSTs, and a more numerous collection of SSTs. Going from the lowest to the highest energies, CTA will provide an angular resolution from $\sim 0.25°$ to $\sim 0.03°$ and a field of view from $\sim 5°$ to $\sim 10°$ [22]. At the lowest energies, where there is some overlap of CTA and *Fermi*-LAT, the former gains the most in sensitivity on short timescales compared to the latter, which on the other hand has a greater sky coverage. Thus, slew speed is important, and the LSTs are designed to slew to any point in the sky within 20 s, while the MSTs can slew to any point in <90 s and SSTs in <60 s.

The baseline array designs proposed to provide the required sensitivity and energy range consist of 4 LSTs and 15 MSTs in the Northern hemisphere and 4 LSTs, 25 MSTs and 70 SSTs in the Southern hemisphere. The SSTs will be deployed only in the South to enhance observations of Galactic plane. Concerning the deployment schedule, the first CTA telescopes will be installed

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[1] https://www.cta-observatory.org

in 2019 on La Palma. A prototype LST is already there, at the site where the two Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes are currently hosted. Transient observations will start early on during construction (in principle with only a single telescope in operation).

6. Follow-Up of Transient Sources with CTA

Within the CTA Key Science Project on transients, those associated with the GWs are the highest priority targets. The observation time devoted to follow up GW transients will range from a maximum of $20\,\mathrm{h\,yr^{-1}}$ of observation time for each CTA site, before array completion, to 5-$10\,\mathrm{h\,yr^{-1}}$ with the full array [22]. Alternative observation modes with CTA, like the so-called "divergent" pointing mode, may reduce the time required to tile a large localization region at a given sensitivity.

The Real-Time Analysis (RTA) pipeline will be able to identify transient sources and automatically issue an alert within 30 seconds from the triggering event collection.

The CTA Consortium will receive GW alerts from the Advanced LIGO/Virgo interferometers, and will follow-up those during dark time with zenith angles less than 70° for 2 hours each, adding exposure time in case of positive detections [22].

The duty cycle of current-generation IACTs is affected, among other factors, by the lunar phase, which prevents observations during full Moon due to the elevated brightness of the sky. SiPM-based IACT cameras have proven to be effective in the detection of cosmic showers under bright moonlight conditions, increasing the duty cycle, although with reduced sensitivity and larger energy threshold. This technological advancement will be utilized in the SCT camera as well as in the SST cameras, therefore opening the possibility of following up GW alerts even during bright moonlight conditions.

The closeness of the MAGIC telescopes and the prototype LST may give the opportunity, if they will be operated in coincidence, to start carrying out a follow-up of GW transients at the CTA Northern site with a system of three large and fast slewing Cherenkov telescopes in stereoscopic mode.

7. Previous Search Strategies with Cherenkov Telescopes

The current-generation IACTs – MAGIC, VERITAS and H.E.S.S. – have been used to perform searches of very high-energy gamma-ray emission associated with GW triggers, as stipulated in Memoranda Of Understanding with the LIGO/Virgo Collaboration.

During the O1 run, MAGIC performed follow-up observations [23] of the event GW151226, later identified as due to a BBH merger. Four MAGIC pointings were manually selected based on visibility, overlap with existing catalogs, and observations of other telescopes. The average exposure per pointing was 42 min. No source was detected during these observations.

The first follow-up at very high energies during the O2 run was performed by VERITAS for the event GW170104, which was due to the coalescence of a 50-solar-mass BBH system at a redshift of 0.2. VERITAS opted for tiling the Northern fraction of the localization map using 39 consecutive pointings each observed for approximately five minutes. VERITAS reports that these observations were sensitive to sources with a flux greater than 50% of the Crab nebula at energies >100 GeV.[2]

H.E.S.S. followed up the binary neutron star merger GW170817 detected during O2, starting 5.3 h after the event with an observational strategy which included folding the localization map for the GW event with a galaxy catalog, and the prioritization of different targets according to their distribution in the sky and observational constraints. The first of the observed regions included the location of the EM counterpart for GW170817 identified later in the optical range. Since no gamma-ray excess was identified in the observed region, upper limits were set between 0.28 and 8.55 TeV [7].

8. LIGO/Virgo Alerts for the Follow-Up

The LIGO/Virgo alert process results in the publication of an alert via the Gamma-ray Coordinates Network (GCN), as for GRBs. In order to summarize the steps of this process, we consider the case of the binary neutron star event GW170817.

The event was recorded 6 minutes after the merger [1, 2], and the GCN alert was sent about 35 minutes later, due to human intervention. A GW skymap of ~ 30 deg^2 (90% c.l.), using information from both LIGO detectors and Virgo, was distributed five hours after the merger. This GW skymap identified a region smaller than the *Fermi*-GBM skymap for GRB170817A, allowing the discovery of the optical transient and the identification of the host galaxy. For comparison, the *Fermi*-GBM initial skymap was distributed 14 seconds after

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[2] https://gcn.gsfc.nasa.gov/gcn3/21153.gcn3

detection [24]. Therefore, partner observatories scanned the Fermi localization region until the improved GW localization area became available. The Swope Telescope, despite its small size, discovered the optical counterpart of GW170817 by targeting galaxies within the GW skymap [25].

9. Conclusions

Based on the present status of observatories and multimessenger observations, briefly reviewed in this contribution, we consider the following directions to be important to maximize the GW-follow-up potential of CTA:

1. Low-latency (≈minutes) GW alerts to partner observatories are critical. Automation is required. For CTA, a FAR higher than 1/month is tolerable as the follow-up of GW triggers only requires $O(1000\,s)$ of observation time.
2. Even a single LST telescope may be able to detect a very high-energy transient on $\approx 100\,\mathrm{Mpc}$ distance scales relevant for GW observations.
3. There is no need for galaxy catalogs, since CTA will have a large multi-deg^2 field of view, albeit with some sensitivity degradation off axis, and the very high-energy sky has a few transients. Therefore, while galaxy catalogs played an important role in the follow-up of GW170817, their utility for CTA follow-up will be limited.
4. Most GW candidates can be followed up assuming a dedicated time of $\sim\ 10\,\mathrm{hr\,yr^{-1}}$ per site and an observation time of 1000 s per event. For BBH mergers, the detection rate could be so high that it will be unfeasible to comprehensively follow up and some prioritization will be needed.
5. Deeper observation of promising GW events is recommended, preferably extending the original observation rather than observing the region of interest in successive nights. A guide for a deeper observation may be the prompt finding of a hint of signal in the RTA.
6. Multimessenger follow-up, via low-latency detection of a GRB counterpart or high-energy neutrinos from a GW source, can be exploited to refine the localization of the source.
7. A multimessenger alert can be sent out by CTA if very high-energy emission from a GW transient is identified with a better localization ($\lesssim 0.1^\circ$ [22]), in order to point other follow-up observatories in the right source direction.

References

[1] B. P. Abbott et al., *PRL* **119** 161101 (2017)
[2] B. P. Abbott et al., *ApJ* **848** L12 (2017)
[3] B. P. Abbott et al., *ApJ* **848** L13 (2017)
[4] B. P. Abbott et al., *LRR* **21** 3 (2018)
[5] I. Bartos et al., *MNRAS* **443** 738 (2014)
[6] I. Bartos et al., *MNRAS* **477** 639 (2018)
[7] H. Abdalla et al., *ApJ* **850** L22 (2017)
[8] M. Ackermann et al., *ApJ* **716** 1178 (2010)
[9] M. Vietri & L. Stella, *ApJ* **507** L45 (1998)
[10] R. Ciolfi & D. M. Siegel, Proceedings of "Swift: 10 Years of Discovery" (arXiv:1505.01420)
[11] D. Lazzati et al., *PRL* **120** 241103 (2018)
[12] B. Patricelli et al., *JCAP* **5** 56 (2018)
[13] S. Kobayashi & P. Mészáros, *ApJ* **589** 861 (2003)
[14] M. H. van Putten et al., *PRD* **69** 044007 (2004)
[15] V. Connaughton, *ApJ* **826** L6 (2016)
[16] F. Verrecchia et al., *ApJ* **847** L20 (2017)
[17] A. A. Abdo et al., *Nature* **462** 331 (2009)
[18] A. Giuliani et al., *ApJ* **708** L84 (2010)
[19] B. Iyer et al., Technical Report, LIGO-India (2011)
[20] K. Somiya et al., *CQG* **29** 124007 (2012)
[21] Y. Aso et al., *PRD* **88** 043007 (2013)
[22] The CTA Consortium, "Science with the Cherenkov Telescope Array", World Scientific, DOI 10.1142/10986 (arXiv:1709.07997) (2019)
[23] A. Carosi et al., AIP Conference Proceedings **1792**, id. 060014 (2017)
[24] A. Goldstein et al., *ApJ* **848** L14 (2017)
[25] D. A. Coulter et al., *Science* **358** 1556 (2017)