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TRANSIENTS

Gravitational waves and electromagnetic transients

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Abstract. The advanced gravitational wave (GW) detector network has started routine detection of signals from merging compact binaries. Data indicate that in a fair fraction of these sources, at least one component was a neutron star, bringing with it the possibility of electromagnetic (EM) radiation. So far, a confirmed link between EM and GW radiation has been established for only one source, GW170817. Joint analysis of broadband multi-wavelength data and the GW signal have yielded rich information spanning fields as varied as jet physics, cosmology and nucleosynthesis. Here, we discuss the importance of such joint observations, as well as current and near-future efforts to discover and study more EM counterparts to GW sources.

Keywords. Gravitational waves—electromagnetic counterparts—transients—multi-messenger.

1. Introduction

The existence of gravitational waves (GWs) from accelerated masses, as being required by the Lorentz transformations, was proposed in 1905, by Poincaré (1906), in analogy to electromagnetic (EM) waves (Miller 1973). A few years later, A. Einstein formulated the field equations of general relativity (GR) (Einstein 1916) leading to the theory of GW. Nearly a century later, a signature GW emitted from a binary black hole (BBH) merger (Abbott *et al.* 2016) (named GW150914) was detected by the advanced laser interferometer gravitational-wave observatory (LIGO) detectors on 14 September 2015. The event commenced the triumph of persistent human efforts to achieve the feat once thought impossible. At the same time, it opened up a new window to observe the Universe with the promise of unfolding many mysteries of nature at its extreme. Later, a joint detection of the GW event GW170817 (Abbott *et al.* 2017a) of a merger of a binary neutron star (BNS) system by Advanced LIGO and Virgo detectors on 17 August 2017, was made. It was accompanied by rigorous observation of EM radiation across the broad spectrum done with tremendous collaborative efforts. This corroborated the expectation, by proving beyond any ambiguity that short gamma-ray bursts (sGRBs) can be produced as an aftermath of compact object merger involving neutron star (NS).

In the Universe, previously seen mainly through EM waves, there are numerous kinds of potential GW sources across a broad spectrum of over 20 orders of magnitude in frequency. It is eminent that following the recent success, extensive exploration, both theoretical and experimental, is to follow for many years to come. This may lead us to obtain numerous insights and fundamental knowledge in a vast range of topics starting from fundamental physics to extreme astrophysics and cosmology. At the fundamental level, it will help us to better comprehend the general theory of relativity and its unification with quantum theory by shedding light on the black hole singularity, cosmological constant, and late-time accelerated expansion of the Universe. GWs emitted during inspiral and the following ring-down of NSs may lead to a significant revelation of properties of their cores and the equation of state (EoS) of the matter inside. GWs can provide

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crucial insight on the nature of dark matter as it interacts by gravitation only. Understanding some of these aspects are related to that of many unsolved topics of cosmology also, those can be benefited with the advancement in GW science. The sGRBs from colliding compact objects are considered among the 'standard sirens' in cosmology (Schutz 1986). The measurement of the luminosity distance relationship of those with the accurate position and polarization information collected by GW detectors, can lead us to a better understanding of the acceleration of the universe and remove the discrepancy between local and early Universe measurement of Hubble constant. This may enable us to make significant progress in comprehending the nature of dark energy.

The GW astrophysics, on the first hand, deals mostly with the interaction and merger of compact objects. It also helps us to extract information about the dynamics and aftermath of the process. These interactions in most of the cases (other than BBHs) also emit EM waves in all possible spectral ranges. It can readily be realized that complementing the GW observation of various sources with the study of their EM counterparts is crucial in getting true insights into them.

In this article, we are going to emphasize the significance of exploration of EM counterpart pertinent to GW observations, discussing in some efforts already made with their outcome and what awaits us in the days ahead in terms of joint exploration of GW and EM waves from space sources, predominantly compact object mergers. In Section 2, we discuss the history of decades of efforts on detecting GWs and how the discovery of GWs changed our view about the Universe. Section 3 discusses the beginning of a new era of multi-messenger astrophysics. In Section 4, we detail the followup of GW170817 by different broad spectrum EM observatories and lastly in Section 5, we summarize the current and future prospects.

2. The brief history

The highly non-linear hyperbolic–elliptic partial differential equations those govern the interplay of matter with the four-dimensional geometry of space and time can be expressed as

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}; \quad \mu, \nu = 0, 1, 2, 3. \tag{1}$$

Here, $G_{\mu\nu}$ represents the second derivative of space–time coordinates and stress-energy tensor $T_{\mu\nu}$ captures the information about energy, momentum and stress associated with all forms of matter and all non-gravitational fields.

Since these equations are very complicated to be solved in full generality, a few solutions have been studied with very restrictive conditions of symmetry. In a weak field situation, Equation (1) has a wave-like solution similar to EM waves which are produced by accelerating dipole charges. However, in the case of gravity, there is no equivalence to a negative electric charge, hence an accelerating quadrupole moment causes a perturbation in space–time that propagates like wave (Misner *et al.* 1973). This wave solution consists of transverse waves of spatial strain that travel at the speed of light, commonly known as GWs. The constant term in Equation (1), $8\pi G/c^4 \sim 10^{-43}$ N^{-1} signifies the very weak nature of wave, as a variation in $T_{\mu\nu}$ must be of $\mathcal{O}(10^{43}$ N) for it to have an observable effect. Hence, linear order perturbation theory was discarded as impractical. At that time of early proposal of existence of GWs, no terrestrial or celestial phenomenon having sufficient equivalent mass quadrupole moment was known to exist, as compact objects such as NSs and black holes (BHs) were not discovered yet.

2.1 *Early efforts and detections*

Bar detection of GWs developed rapidly through the 1960s, however, contradictory results dampened enthusiasm. Efforts were devoted in technically excellent bars such as *ALLEGRO*, *AURIGA*, *EXPLORER*, *NAUTILUS* and *NIOBE* over the subsequent decades (Saulson 1995; Collins 2004). Meanwhile, prototypes by Rainer Weiss, Ronald Drever, Robert Forward (Forward 1978), and many others demonstrated that interferometry could also achieve the sensitivities desired for GW detection. Interferometry promised better fundamental noise source characterization and broadband operation and hence a single instrument could observe in a wider frequency band.

The search for GWs, however, gained momentum when its existence was indirectly supported by the orbital decay of the binary pulsar (binary NS) PSR 1913+16 (Hulse & Taylor 1975). This system was discovered from a radio signal by Hulse and Taylor in 1974. Over the years, its period has been repeatedly measured, demonstrating that its orbital decay is consistent with GR predictions on energy lost by the emission of GWs (Taylor & Weisberg 1982). In 1993, Hulse and Taylor were awarded the Noble Prize for

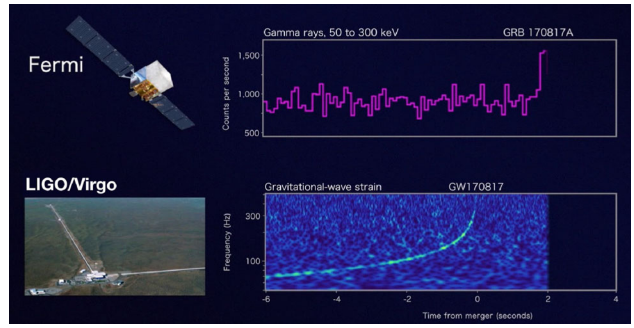

Figure 1. Simultaneous signal arrival from GW170817 event at Top: *Fermi* satellite in γ-ray band and Bottom: in LIGO/Virgo GW detectors. Each sent out an independent alert. Image Credit: NASA GSFC & Caltech/MIT/LIGO Lab.

the indirect proof of the existence of GWs. The discovery of this new type of pulsar opened up new possibilities for the study of gravitation and that of detection of GWs as well. Since the discovery of PSR 1913+16, it has been known that compact object binaries exist in our galaxy, and that at least some of them will decay by emission of GW to merge in less than a Hubble time.

The existence of GW emission from compact object binaries was spectacularly confirmed by the detection of the BBH system GW150914 in Observation Run 1 (O1)[1] of LIGO/Virgo Collaboration (Abbott *et al.* 2016). Since then, a total of 90 compact binary coalescence (CBC) candidate signals have been identified whose (estimated) probability of astrophysical origin is > 0.5 (Abbott *et al.* 2019, 2021a; The LIGO Scientific Collaboration 2021a,b). This allowed us to study extragalactic objects, which were previously unknown to humankind. Coincidentally, around the first gravitational wave detection, a low confidence EM event was also observed by *Fermi*-LAT (Connaughton *et al.* 2016). However, due to the lack of theoretical modeling (for BH–BH merger) and insufficient signal-to-noise ratio (SNR), the event was not deemed as an EM counterpart event, rather a cosmic coincidence or an instrument artifact.

2.2 *Maiden detection of EM counterpart from a GW event: GW170817 and its significance*

Theoretically, the mergers of binary compact object are more likely to have an EM counterpart if one of the objects is a NS. Due to the absence of EM observations in O1, the rates of NS–NS/BH–NS mergers were estimated based on the population models and previous observations of sGRBs (Fong *et al.* 2015). It was estimated to be around ~ 0.2–300 per year, assuming Advanced LIGO/Virgo reach their full design sensitivities (Abadie *et al.* 2010; Dominik *et al.* 2015). Although sGRBs are arguably the simplest and common EM counterparts, their measured rate within the Advanced LIGO/Virgo sensitivity volume is probably less than one per year for the total sky (Metzger & Berger 2012).

During the second observing run (O2) of the GW detector network, the detection (Abbott *et al.* 2017a) of GW signal from a BNS merger event, named GW170817, by the advanced LIGO/Virgo detectors, turned the anticipation into reality. With a delay of 1.7 s, *Fermi* detected a GRB near the location obtained by LIGO/Virgo localization (Abbott *et al.* 2021b). A γ-ray signal was also found independently in the data of the *INTEGRAL* satellite (Savchenko *et al.* 2017). Figure 1 shows the simultaneous arrival of the GW and EM signals in both ground-based, kilometer-scale laser interferometer and space-based high-energy detector on-board *Fermi*, respectively. This is a first-of-its-kind event opening a new era of astrophysical observation. This event also narrowed down alternate gravity theories which cannot justify such an event in detail. Tensor–vector–scalar gravity (TeVeS) (Bekenstein 2004) was one such well-known example, which was falsified (Boran *et al.* 2018) after the GW170817 event.

Based on the sensitivity region and the response function of LIGO/Virgo detectors along with the fact that one BNS merger event was observed during the time duration of O1 and O2, we can estimate the NS–NS merger rate in a given volume. The volumetric rate therefore was estimated to be around 110–3840 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (Abbott *et al.* 2019), which translates to roughly NS–NS merger rate of = 6–120 yr^{-1} (Abbott *et al.* 2021b) within the full sensitivity region of LIGO/Virgo detector. Similarly, the absence of NS–BH observation during O1/O2 run, an upper limit of NS–BH merger rate of 600 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ was estimated (Abbott *et al.* 2019; Metzger 2019).

GW170817 marks a true start of multi-messenger astronomy, where an event was observed by a network of both GW detectors and EM observatories. An extensive multi-wavelength campaign followed, ranging from radio frequencies to γ-rays with the help of ~ 70 EM observatories around the planet and from space (Abbott *et al.* 2017b). The detections and the measurements by different instruments as well as the

[1]GW150914 was detected 4 days before the official start of O1.

non-detections, helped us put better bounds on several parameters.

Analysis of the GW data supports the hypothesis that the event GW170817 is the consequence of a merger of two NSs of masses roughly between 0.86 and 2.26 $M_\odot$ which occurred at a luminosity distance of 40 ± 8 Mpc (Abbott *et al.* 2017b). Furthermore, the multi-wavelength EM data show that the merger caused sGRB (GRB 170817A) (Abbott *et al.* 2021b; Goldstein *et al.* 2017) in a galaxy named NGC 4993, which was followed by a kilonova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta (Abbott *et al.* 2017b). The EM location and other parameters were consistent with the GW extracted parameters. Along the timeline of the event, different mechanisms cause radiation of different wavelengths, which is un-layered by first of its kind multi-messenger observations.

Relative to the time of merger t_c as measured by GW data, the first γ-ray counterpart was reported at $t_c + 1.734$ s. This initiated a search from other EM observatories and at $t_c + 10.87$ h (Coulter *et al.* 2017), $t_c + 9$ d (Margutti *et al.* 2017) and $t_c + 16$ d (Hallinan *et al.* 2017) first optical, X-ray and radio counterparts were observed, respectively. Figure 2 and Tables 1–6 in Abbott *et al.* (2017b) detail the timeline of the observation in different parts of the EM wavelength range during the discovery and followup of the event. Some details of the multi-wavelength observations are included in Section 4 of this article.

It is to be noted that no confirmed neutrino counterpart for the GW event has been found yet. However, a high-energy neutrino ($\sim$290 TeV) counterpart for γ-ray blazar TXS 0506+056 was detected on 22 September 2017 named IceCube-170922A (IceCube Collaboration *et al.* 2018). Therefore, the possibility of future neutrino counterparts for a GW triggered GRB cannot be ruled out.

2.3 *Post GW170817 searches*

Post GW170817 the LIGO/Virgo detectors have observed many more CBC events. Particularly, in the third observation run (O3), with more sensitivity, the LIGO/Virgo detectors observed 35 new such GW occurrences, significantly more than the previous two runs. One of the highlights was the event GW190425. Based on its mass estimates, it is likely a BNS merger. However, unlike GW170817, for this event no EM signals are detected and no confidence measurement of tidal deformations are observed yet. We also observed other promising NS–BH mergers and mass-gap mergers like, GW190426 (Abbott *et al.* 2021a), GW190814 (Abbott *et al.* 2020, 2021b), GW200105 and GW200115 (Abbott *et al.* 2021c). Unfortunately for 13 of such EM promising events no confirmed EM counterpart has been observed, partly, because these

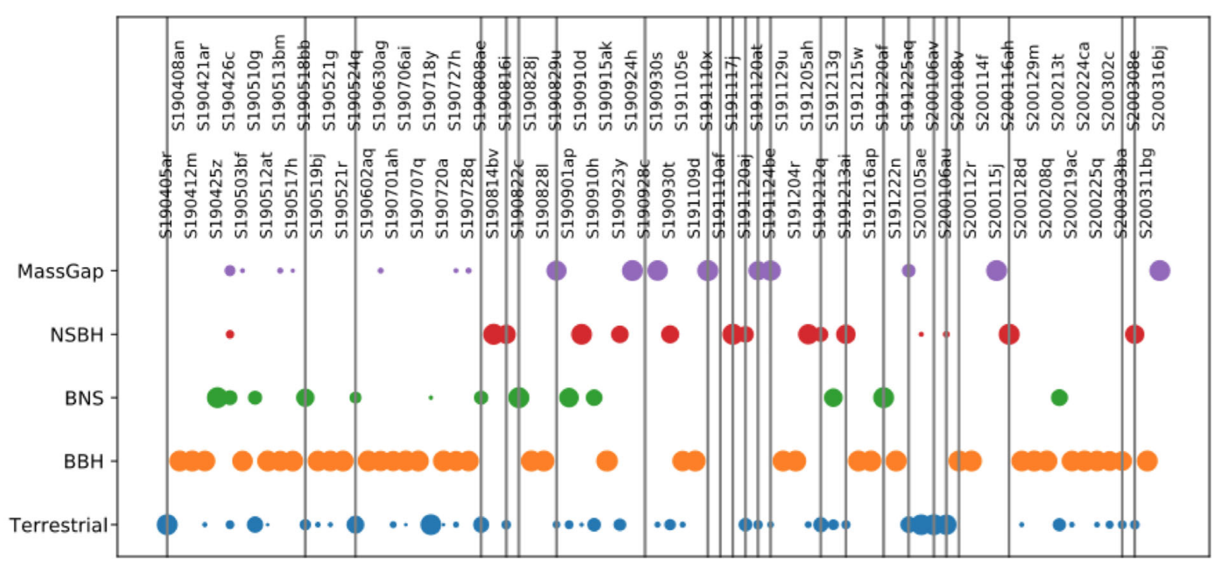

Figure 2. Public alerts and follow-up investigations of O3a GW candidates. The size of the colored solid circles corresponds to the estimated probability of different events (as mentioned on the *y*-axis). The crossed events are those alerts that were eventually retraced. The alert names do not have the prefix 'GW' as that is only assigned after complete analysis. Data: https://gracedb.ligo.org/superevents/public/O3/.

events being outside the sensitivity of the current instruments. Figure 2 shows the public alerts in the first half of O3 (O3a), some of which were investigated by EM observatories. Although there is no currently accepted models to explain EM radiations from some of these events (Zhu *et al.* 2021), their silence could share few insights on some of their properties. As discussed in Section 4.1.3, the absence of EM counterparts help us establish bounds on the merger rate and luminosity function of the brightness of such events.

While several of these CBC events do not allow separate independent studies, their parameter distributions have left us with some curiosity (The LIGO Scientific Collaboration 2021b). It is unclear why the masses of the CBC events have gaps and priority to certain values. For example, there is a clear drop in the number of objects just above 2 solar masses and if there is a gap, it starts above 75 solar masses — far higher than expected. The presence of Heavier NSs suggests that EoS cannot be too soft and larger NSs mean we can rule out stiff EoS. Insights into these puzzles will likely be explored in upcoming observation runs with more sensitivity and more data.

3. GW and the dawn of multi-messenger astronomy and astrophysics

Simultaneous GW and EM radiation analysis from any astrophysical transient source should provide us valuable and complementary insight into the source. While the bulk motion of mass within an astrophysical source can be traced through GW, the EM waves can help us probe the interaction of hot matters, such as acceleration, friction, shock, nuclear reactions and many others. In addition, it can infer the presence and configuration of magnetic field and interaction of particles in the hot plasma with the field.

The merger of stellar-mass BHs and NSs are the primary sources of interest for GW detection. The signal from the spiraling objects, lasting from a few seconds up to a few minutes, chirps upwards in frequency peaking as the two objects merge. For BBH merger, the formation of final black hole is confirmed with observation (Abbott *et al.* 2021d). For a NS–BH merger, the final object should always be a BH. EM counterpart from such event though suspected (Abbott *et al.* 2020) is not confirmed yet. The merger of two black holes is not expected to produce EM counterpart as there is no matter. Though there are theories that the surrounding material from the accretion disks being influenced by the merger dynamics can emanate EM waves (see Kelly *et al.* 2017). The collisions of two neutron stars (BNS), or a neutron star and a black hole (NS–BH) are the most likely sources for emission of both gravitational and EM waves. In an NS–BH system with a large mass, as the BH is always supposed to swallow the entire NS, there should not be any EM signature. For lighter NS–BH systems, the NS may be tidally disrupted before plunging into the BH (Foucart *et al.* 2018) and release of a considerable amount of mass and hence EM counterpart is expected.

3.1 *BNS merger*

For lower mass binaries, i.e., BNSs, following the merger, a remnant object is created that is $\geq 90\%$ of the masses of the two individual objects. For BNS merger events, the signal is observed for a relatively longer period of time. Till now there is only a single detection of combined GW and EM emission from a BNS merger, namely, GW170817.

For a long time, BNS mergers were considered to be promising sites of heavy *r*-process nucleosynthesis and site of origin of heavy elements (e.g., Côté *et al.* 2018; Metzger 2019). The current capabilities of multi-messenger observations may provide significant insights into the progenitors (e.g., Burns 2020) of astrophysical phenomena such as GRBs and the origin of heavy elements. GW170817 already provided some observational evidence supporting this scenario (Hotokezaka *et al.* 2018).

There is a 4σ to 6σ disagreement between measurements of Hubble constant (e.g., Di Valentino *et al.* 2021). GWs, used as standard sirens, can give a measurement of the distance of a source and joint EM observations can provide the source redshift. The combination is ideal for unambiguous measurement of the Hubble constant (Schutz 1986). The first of its kind joint analysis of the GW170817 provides us the unique opportunity of measuring the absolute distance to the source directly from the GW measurements event ($\sim$40 Mpc), and hence the distance to the galaxy NGC 4993. At the same time, recession velocity has been inferred from measurements of the redshift using the EM data. Hence an independent measurement of the local Hubble constant is found to possibly be constrained to high precision (Abbott *et al.* 2017c)

The EoS that governs the tidal deformation of NSs can be studied by analyzing GW data as these deformations enhance the GW emission and thus accelerate the decay of the quasicircular inspiral. Based on the mass and radius of NSs, the hard EoS conditions were ruled out, when the radius ($R_{1.4}$) of NS assuming mass 1.4 $M_\odot$ was estimated to be $R_{1.4} \lesssim 13.5$ km (Abbott *et al.* 2018). Further joint observation of EM and GWs of mergers should shed light on the neutron-star EoS, helping us better understand the quantum chromodynamics and, ultimately, the standard model of particle physics.

The combined GW and EM observation can reveal significant insight into the physics of the BNS merger events by shedding light on the emission process, particle acceleration mechanism, jet emanation, propagation and the progenitor itself. Although GRB170817A is extremely weak compared to sGRBs (the isotropic equivalent γ-ray energy is smaller than the weakest sGRB by more than two orders of magnitude), the observed γ-rays indicate that a relativistic outflow was been produced (Kasliwal *et al.* 2017). The X-ray observations disfavor simple top-hat jets and support the scenario where both the X-ray and radio emissions are the afterglow of an outflow or structured jet. Continued monitoring will provide even more information for constraining post-merger models, as shown in Figure 3.

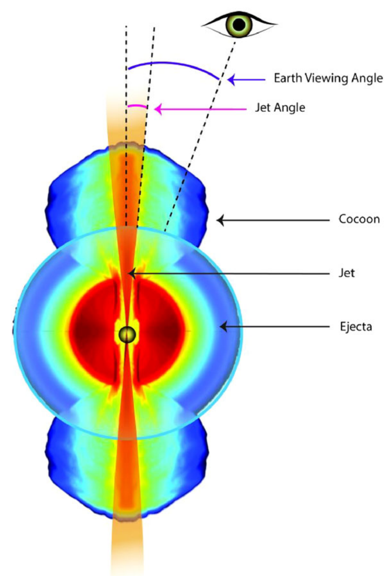

Figure 3. Aftermath of the merger of two NSs. Ejecta from an initial explosion formed a shell around the BH formed from the merger. A jet of material propelled from a disk surrounding the BH first interacted with the ejecta material to form a broad 'cocoon'. Credit: Sophia Dagnello, NRAO/AUI/NSF.

3.2 *Other possible sources of GW and EM waves*

3.2.1 *SMBHs* Supermassive Blackhole (SMBH) coalescence due to the collision of galaxies is another prominent candidate of both GW and EM counterparts, as the significant amount of gaseous material involved should emit EM signals. Several EM counterparts involving precursors, prompt and afterglow phases of resulting transient have been proposed (Schnittman 2011)

BH remnants from short-lived massive stars and white dwarfs closer to a SMBH are regular phenomena. Detection of those is possible through gravitational radiation of their interaction with the SMBH. White dwarfs may be tidally disrupted by the SMBH in their late inspiral and provide both GW and EM counterpart. The combination of distance measured from those GWs and EM redshift from these sources should be invaluable for precision cosmology (Haiman *et al.* 2009).

3.2.2 *Rotating hypernovae* Rapidly rotating hypernovae implicated in long-duration gamma-ray bursts, magnetar progenitors, etc., may emanate strong GWs (Ott 2009). These GW forms identified in coincidence with EM observations should provide a better insight into the interior dynamics of those core-collapsed supernova.

3.2.3 *BBH merger in active galactic nuclei* A plausible EM candidate of BBH merger has been proposed that coincides with the event GW190521 (Graham *et al.* 2020). Zwicky Transient Facility (ZTF) detected an optical source within the localization region of the S190521g trigger (later changed to GW190521), however, the uncertainty in sky position of the GW localization was hundreds of sq. deg., and so the association could not be confirmed. Since there is no concrete theoretical explanation for for EM emission from a BBH, a possible explanation was suggested by Graham *et al.* (2020). According to them, the merging of the two smaller BHs might have sent the newly formed intermediate mass BH on a trajectory that hurtled through the accretion disk of an unrelated but nearby supermassive black hole, disrupting the disk material and producing a flare of light. This hypothesis could be tested if the flaring is repeated ~ 1.6 yr (assuming typical parameter space) later. This is unlike *Fermi* observation of BBH merger event (Connaughton *et al.* 2016), where both the error region and the confidence was poor enough to confirm a counterpart. We are yet to observe an EM counterpart from a BBH merger.

4. EM counterpart of GW: detection and future exploration

In this section, we will briefly discuss the efforts of detection of EM counterparts of GW and the outcome so far along with the ongoing and upcoming endeavors.

4.1 *Optical studies*

Optical studies of sGRBs produced by mergers are useful in inferring the mechanism of two distinct components of emission from them. One of which is the afterglow emission, produced by the interaction of the relativistic jet with the surrounding medium. Another component is kilonova, which is powered by the radioactive decay of the sub-relativistic material ejecta. These are predicted both from dynamical interaction during the merger and from the accretion disk after merging. The latter contains heavy nuclei that decay and produce a emission in the optical and infrared shortly after the coalescence of the compact objects. These events are thought to be isotropic and so are easily detectable than the beamed sGRBs.

4.1.1 *How to study optical counterparts* The prime challenge in the identification of EM transients associated with GW signals is the relatively poor GW sky localization. This capability relies on the number of detectors and the size of the baseline. With two detectors the localization area is of the order of hundreds to thousand sq. deg., which can be improved by a factor of ten by adding more detectors. With hundreds of variable sources within a sq. deg., scanning a large area of the sky and comparing with an existing catalog of sources to possibly concentrate on a few counterpart candidates is challenging. Spurious detections due to instrument artifacts add to the difficulties. After satisfactory cleaning up, few remaining candidates are followed up to identify a possible GW–EM counterpart spectroscopically. After the detection of prompt emission, observing the sky error box with the cadence of a few days is necessary in order to build the light curves to catch the right source. Depending on the distance of the GW event and the relative area of the sky to be searched, two different approaches are taken. First, if the source is nearby and the sky area is small or moderately large, then imaging each individual galaxy in the region is the most effective approach. On the other hand, if the source is at a relatively large distance, and the sky volume is larger, then the number of galaxies becomes too big and observing each individual galaxy becomes too expensive in terms of telescope time. In the later scenario, blind search covering the whole field is more effective and wide-field telescopes are preferable.

Compact stars mergers, if the associated jet axis is oriented at a small angle to the observer, are expected to be detected as sGRBs and following multi-wavelength afterglows. For the faint sGRB from GW170817, the viewing angle is slightly misaligned (10–30°) with respect to the polar axis (Mooley *et al.* 2017).

4.1.2 *Optical surveys and detections* Optical surveys of GW objects have been performed during O1 and O2 LIGO and Virgo Collaboration (LVC) scientific run by numerous telescope facilities and teams. This includes the Swope supernova survey telescope, ESO-VLT Survey Telescope (VST), Antarctic Survey Telescopes, the GRAvitational Wave Inaf TeAm (GRAWITA), Dark Energy Camera (DECam), DLT40, REM-ROS2, HST, etc., (Abbott *et al.* 2017b). The Swope supernova survey telescope detected the kilonova (Coulter *et al.* 2017) and located it at NGC 4993, an S0 galaxy at a distance of 40 mega-parsecs. The Antarctic Survey Telescopes (AST3) at Dome A, Antarctica also detected the object and located it at the same galaxy and measured the brightness and time evolution of optical properties and characterized the source along the line of prediction by merging BNSs model (Hu *et al.* 2017). The GRAWITA team has been successfully observing the optical counterpart of GW170817 (Grado 2019) using VLT and REM telescopes. The spectroscopic followup in optical/infrared of the related kilonova AT2017gfo provided the first compelling observational evidence of such object and establishes BNS mergers as the dominant sites for the production of *r*-process heavy elements in the Universe. We restrict ourselves from including other important observations due to lack of scope of detailing in this article.

4.1.3 *Results from O3* After a successful run in the second phase (O2) with seven BBH merger and one BNS merger event detection, LIGO/Virgo opened up its eyes to the vast sky in April 2019 for the third time (O3) (Abbott *et al.* 2019). Inspired by the successful observation run for the GW170817, many such surveys are done in the O3. Although there has not been any fruitful detection, the non-defections themselves help us gaining important lessons on the GRB rate and observation constraints. In the O3 LVC

Table 1. Estimates on BNS rates from optical surveys, GW observations, galactic double neutron star observations and population synthesis results, as described in Andreoni *et al.* (2021). The third column represents the confidence of the rate estimates. In some articles enough information is not mentioned about the confidence, hence the entry is left blank.

Method	Rate (Gpc^{-3} yr^{-1})	Confidence	Reference
Optical survey KN	$R < 900$	–	Andreoni *et al.* (2021)
	$R < 800$	3σ (99.7%)	Kasliwal *et al.* (2017)
GW BNS mergers	$80 < R < 810$	90%	Abbott *et al.* (2021b LIGO/Virgo)
sGRB	$71 < R < 1162$	90%	Della *et al.* (2018)
	$60 < R < 360$	1σ (68.3%)	Dichiara *et al.* (2020)
Population simulation	$300 < R < 1200$	90%	Chruslinska *et al.* (2018)
Galactic double NS	$70 < R < 490$	95%	Kim *et al.* (2015)
	$260 < R < 610$	90%	Pol *et al.* (2020)

run important results regarding optical counterpart observation of 13 GW triggers involving at least one NS are presented by Kasliwal *et al.* (2020). With ZTF and GROWTH surveys they find the upper limits to constrain the underlying kilonova luminosity function and compare them with that obtained from radiative transfer simulation. This study is particularly important as those are not well understood theoretically, to be compared with the observational results. By comparing these luminosity function constraints they try to find its implications on the kilonova parameter space. This comparison suggests that a few KNe are expected to have ejecta mass ($M_{ej} \leq 0.03\ M_{\odot}$ or $X_{lan} > 10^{-4}$ to satisfy the ZTF constraints.

A similar comparison of luminosity function constraints to Dietrich *et al.* (2020) KNe grid indicates that some kilonovae are expected to have dynamical ejecta mass $(M_{ej,dyn}) < 0.005\ M_{\odot}$ or post-merger ejecta mass $(M_{ej,pm}) < 0.05\ M_{\odot}$ or half opening angle of red kilonova component $(\phi) > 30°$. Andreoni *et al.* (2021) using ZTF capability of identifying rapidly fading transients independently of external GW triggers have found afterglows with and without known gamma-ray counterpart, and few fast-declining sources likely associated with GRBs. However, with their non-detection of any kilonovae they constrain the rate of GW170817-like kilonovae to $R < 900\ Gpc^{-3}yr^{-1}$. Table 1 shows comparison of merger rate estimates by different studies.

4.1.4 *GIT followup of LVC events* GROWTH-India telescope (GIT), which is a 0.7 m planewave telescope situated at the Indian Astronomical Observatory (IAO), Hanle, $\sim$4500 m above sea level (Prabhu 2000), has played a significant role in study of EMGW events during O3 run of LVC. GIT is set up as a combined effort of Indian Institute of Technology Bombay (IITB) and Indian Institute of Astrophysics (IIA), Bangalore. This planewave telescope is accompanied by Andor iKon-XL 230 CCD camera.[2] The 16.8 megapixel sensor provides a large field of view, which gives it the ability to tile up the well localized events detected by LVC for KNe search. Moreover, the automated observing abilities of GIT are vital for automated response to such time-constrained followups.

Soon after restarting the O3 observation run, LIGO/Virgo detected the second BNS merger event named GW190425z (Abbott *et al.* 2021b) on 25-04-2019. Based on the preliminary information LVC classified this event as a probable BNS event. On the very next day, LVC detected another low latency event S190425c with non-negligible probability of being a BH–NS event. The list is populated till the LVC continued the O3a run up to 01-10-2019. During the O3a run LVC detected a total of 23 merger candidates,[3] five of which were found to be noise artifact after further inspection of LVC data and were retracted. Among the rest, 10 events had at least one NS as a merger candidate as per the preliminary classification. Given the huge localization for most of these events, GIT followed up all but S190426c event in the targeted mode where data were accumulated for interesting candidates discovered by other observatories. The summary is provided in Table 2.

For S190426c, coordination was made with Zwicky Transient Facility (ZTF) and Dark Energy Camera (DECam) of Cerro Tololo Inter-American Observatory (CTIO) to cover up the whole location. High density localization probability region is tiled up, in search of the optical counterpart of the event, and five

[2] https://sites.google.com/view/growthindia/about.

[3] https://gracedb.ligo.org/latest/.

Table 2. Followup summary of LVC events observed by GIT during the O3a run. GIT followed up a total of six events in either tiled or targeted mode. In tiled mode, we tile up the localization to search for counterpart while in targeted mode we followed up interesting candidates put up by other large observatories. The first column in the table represents the preliminary names of event from LVC. Second column denotes the most probable event type. Third column shows our followup type: either tiled or targeted. The last column has all candidates we followed for these events.

Event name	Event type	Followup type	Candidates followed
S190425z	BNS	Tiled, Targeted	ZTF19aaryopt, ZTF19aasckkq ZTF19aarwywe, ZTF19aaryqcn, ZTF19aarykkb, ZTF19aarzaod,
S190426c	BHNS	Tiled, Targeted	ZTF19aasmloi, GRAWITA_J220, GRAWITA_J215, ZTF19aasmddt
S190814bv	NSBH	Targeted	DG19fcmgc, DG19wgmjc, DG19rzhoc, DG19wxnjc
S190901ap	BNS	Targeted	ZTF19abxdvcs, ZTF19abxgatn ZTF19abvkfjd, ZTF19abwscnx, ZTF19abxdrvp, ZTF19abxdtht, ZTF19abwsmmd, ZTF19abwtibv, ZTF19abwvals, ZTF19abvislp, ZTF19abvionh, ZTF19abvixoy, ZTF19abvizsw, ZTF19abvjnsm,
S190910d	NSBH	Targeted	ZTF19abyfazm, ZTF19abyfbii, ZTF19abyffeb, ZTF19abyiwiw
S190910h	BNS	Targeted	ZTF19abygvmp, ZTF19abyheza, ZTF19abyhhml, ZTF19abyileu, ZTF19abyirjl

Table 3. Comparison of key parameters of GRB missions. *Fermi*-GBM discovered the largest number of GRBs due to its high 'grasp', defined here as the product of effective area and field of view. *GECAM* has a slightly larger grasp. *AstroSat*-CZTI is currently one of the key GRB detection satellites, but is not listed here due to its highly variable effective area over the sky.

Mission	Energy range (keV)	Effective area (cm^2)	FoV		Grasp (cm^2 sr)	Sensitivity (1-s, 5σ)	
			Sky fraction	(sr)		erg cm^{-2} s^{-1}	ph cm^{-2} s^{-1}
Daksha (single)	20–200	1300	0.7	8.8	11435	4×10^{-8}	0.6
Daksha (two)	20–200	1700	1	12.6	16336	4×10^{-8}	0.6
Swift-BAT	15–150	1400	0.11	1.4	1960	3×10^{-8}	0.5
Fermi-GBM	50–300	420	0.7	8.8	3695	20×10^{-8}	0.5
GECAM-B	6–5000	480	0.7	8.8	4222	9×10^{-8}	–
SVOM/ECLAIRs	4–150	400	0.16	2	800	4×10^{-8}	0.8

promising candidates were found. However, none of the candidates were found to be evolving like a kilonova. No counterpart in the region followed by GIT up to a depth of 21.3 mag is found. Using these non-detections, KNe models (Kumar *et al.* in preparation) is constrained. Furthermore, following up of S190814bv, S190901ap, S190910d, S190910h events in the targeted mode are done, which helped in filtering out a few irrelevant candidates posted by other observatories (see Table 3 for details). Result of detailed photometry of can be found in Kasliwal *et al.* (2020).

4.2 *X-ray/γ-ray*

Among all the sources of GWs having EM counterpart with the mergers involving neutron stars producing sGRBs are going to be the main object of focus in current and future X-ray γ-ray surveys as part of multi-messenger astronomy. sGRBs are very short lived (<2 s) typically have the time period of a few hundred millisecond, so the high-energy instruments are required to have specific abilities to analyze these sources.

4.2.1 *Prompt and afterglow emission corresponding to GW170817* The sGRB corresponding to GW170817 detected by hard X-ray/soft gamma-ray *Fermi*-GBMdetectors, on-board *Fermi* satellite (Goldstein *et al.* 2017) and in SPI-ACS (Savchenko *et al.* 2017) on-board *INTEGRAL*. It was the very first detected EM counterpart associated with GW emission. The signal was in the form of a emission spike of about 0.5 s, followed by a much weaker and softer signal observed by *Fermi* having t90 (i.e., the time over which a burst emits from 5% of its total measured counts to 95%) of 2 ± 0.5 s. Given the approximate distance of the source ~ 40 Mpc measured by LIGO/Virgo, the total fluence value and hence the isotropic energy were inferred from the prompt phase observation. The isotropic equivalent gamma-ray energy was found to be three orders of magnitude lower than the faintest sGRB observed. Hence, it was attributed to the off-axis configuration of the sGRB (Schutz 2011), resulting suppressed emission along the typical viewing angle of the jet. The first detection of such event helps us to confirm the theoretical predictions about compact object merger as a possible source of sGRBs. Apart from that, the observation has deeper implications demanding further theoretical understanding on the front. First, the delay between GW event of BNS merger and the observed sGRB trigger is important in shedding light on the process related to emission and jet — namely, jet injection time, jet/cocoon breakout time and the time taken to reach transparency (Zhang 2019). The observed gamma rays in the afterglow (Kasliwal *et al.* 2017) implied the necessary presence of a structured outflow outside the jet core. Evidently, the detection of a single such event is not sufficient to distinguish between the two competing models that explain the process. One model is, where the emission is within a less energetic wide-angle jet ‘wings’ around the jet core, and second model is, the shock breakout emission of the cocoon emerging from the ejecta. A larger statistical sample of the BNS/NS–BH mergers is indispensable to further constrain these models, needing more future endeavor along this direction.

About 4.6 h after the GW trigger *MAXI* telescope got the first observation of soft X-ray yielding upper limit on the 2–10 keV band, followed by *Swift*, *NuSTAR* and *CXO* in hours to days following the trigger corresponding to deeper upper limits. CXO detected the first X-ray afterglow 9 days after the merger (Troja *et al.* 2017). Along with the radio, the X-ray afterglow showed a trend of continuous rising to the peak after 130 days and then a rapid fall. It was the clear signature of sGRB observed off-axis and inferred many things about the host galaxy, the BNS local environment and the source location in the galaxy. Further strengthening the connection between sGRBs and BNS mergers, the estimated rate of BNS merger obtained from single case of GW170817 was found to be consistent with beaming corrected local rate of sGRB (~ 1000 Gpc^{-3} yr^{-1}).

The first and only joint detection of sGRBs with a GW event (GW170817) offered an unprecedented opportunity of observation, like, confirmation of the discovery of an EM counterpart to a GW source, BNS merger to be localized in the local Universe, first observations of a structured relativistic jet observed from the side, definitive detection of a kilonova, etc. These events and the corresponding efforts in observing it in high energy have also led us towards clear comprehension of the future need on the specifications of the detectors/instruments.

4.2.2 *Other attempts: cross searches between GRBs and GW* There have been several attempts at understanding these sources indirectly, through EM detection of events with similar signature as of GW170817. Non-detection in many cases also has significance in constraining models. There are blind searches for Kilonovae (that are untriggered by GRBs or GW events), which have been actively monitored in optical band. Similar efforts have been made in the X-ray spectrum as well. Since GRB170817A was detected by *Fermi* and *INTEGRAL* independently of the GW event, it was expected that there are similar sGRBs detected in the past. A searched through the *Fermi*-GBMcatalog to find GRBs similar to GW170817, observed 13 of such events. But due to the lack of redshift information on 12 of these GRBs, no further conclusion could be made. The other GRB – GRB150101B has been thoroughly analyzed by several groups over the years. The prompt emission and several afterglow emission properties mimic those of GRB170817A, and a cocoon breakout model has been used to explain the emission mechanism.

Recently, the attempts to search for sub-threshold GW events, coincident with *Fermi* and *Swift* detected GRBs, have made significant progress. Although no evidence was found for any GW like event coincident with the GRBs, these results have helped constrain the population of the low luminosity sGRBs. In the future, cross searches between GRBs and GW can help to detect these events in real time and also to constrain the emission models.

4.2.3 *Current and future relevant X-ray/γ-ray missions* The existing space-based instruments such as *Chandra*, *XMM*, *NuSTAR*, *Fermi*, *IXPE*, etc., are currently active for the survey and GW followup in X-ray/γ ray. Many sensitive satellites, like *Swift*, *INTEGRAL* or *Fermi*, failed to detect GRB 170105A. This demonstrates the importance of developing more broadband, truly all-sky monitors. This had lead to more rigorous involvement in the further such studies using both existing facilities and future space instruments.

While searching for GW170104, *AstroSat*-CZTI covered 50.3% of the probable region in the sky. However, it failed to detect any excess hard X-ray emission, temporally coincident with the event. Whereas, the optical lightcurve of ATLAS17aeu is found to have an explosion offset from the GW trigger by 21.1 ± 1.1 h. A combined study of AstroSat CZTI and IPN localizations of the GRB, finally found that ATLAS17aeu is the afterglow of GRB 170105A (Bhalerao *et al.* 2017).

Many research activities are going on to find innovative ways to improve the observation and survey process. At the same time, new facilities for EM followups are taking place. There have been a few completed and some future proposals are in the pipeline for some dedicated medium class mission pertaining to observation of the frequencies corresponding to EM counterparts of GW.

Many new instruments have been launched and proposed, particularly for high-energy GW counterpart survey and followup study, such as *GECAM* (Zhang *et al.* 2019) from Chinese adademy of science (CAS); *SVOM*, a small X-ray telescope satellite (Paul *et al.* 2011) jointly planned by CAS and French Space Agency; *Daksha*, an all-sky X-ray/γ-ray monitor from ISRO India. Also, there are some proposed cubesats, such as Burstcube (Racusin *et al.* 2017), Camelot (Werner *et al.* 2018), BlackCAT (Chattopadhyay *et al.* 2018), etc.

Studies of the high-energy transients (primarily GRBs), often encounter a bottleneck due to the ambiguity on the spectral properties and its origin. The only way to unravel the true mechanism of GRB emission, is the polarization of the hard X-ray/soft-gamma-ray part of the spectrum. AstroSat CZTI has progressed a lot on that direction along with some other international missions, like Polar. In Table 2, we present the values of various detection parameters relevant to observation.

4.2.4 *Daksha* The discovery of GRB 170817A coincidentally with GW170817 has been one of the milestone observations confirming long assumed short-gamma-ray burst (sGRB) and BNS merger. But this discovery was also important to raise newer questions and pointing out the shortcomings of the existing observational facilities. A sGRB with such low isotropic energy ($E_{\rm iso}$) was never seen before. This GRB was detected only by *Fermi* and *INTEGRAL* and if it were even 30% fainter, it would have been missed entirely (see for instance Goldstein *et al.* 2017). Other satellites like *Swift*-BAT and *AstroSat*-CZTI missed the event as the source was occulted by the earth. Thus, for discovering more such counterparts we need next-generation missions with higher sensitivity and better sky coverage. One such proposed mission is *Daksha*. Scaling from GW170817 and the expected distances of future BNS detections, the sensitivity of an ideal mission to detect the EM counterparts to gravitational wave sources nearly 1×10^{-8} erg cm^{-2} s^{-1}. An 'open detector' with such sensitivity is impractical. Hence, in *Daksha* an alternative way has been considered, i.e., a combination of an order of magnitude better sensitivity as compared to existing missions, with an optimal sky coverage. The sensitivity of *Daksha* will be 4×10^{-8} erg cm^{-2} s^{-1}. *Daksha* will also cover the energy range 1 keV–1 MeV, which will help us to model the 'Comptonised spectrum' of various kind of GRBs, like 'classical' (on-axis) long and short GRBs, fainter high redsifted classical GRBs. Recent studies (Oganesyan *et al.* 2018) have also shown that prompt emission from classical GRBs exhibits a low energy break ($\sim$3–22 keV). The low-energy band of *Daksha* will also be useful for the bursts that are seen at higher off-axis angles, and distinguishing between thermal and nonthermal spectral components. The high-energy coverage of *Daksha* will help us to constrain the spectral parameters (β, $E_{\rm peak}$), which are currently difficult to constrain with the existing instruments.

A satellite in low-earth orbit has effective spatio-temporal coverage of nearly 50–55%. The situation improves drastically after including the *Daksha*. In such a case, the joint coverage increases to about 87%: a gain of almost a factor of 1.5 over a single satellite. *Daksha* will attain an angular resolution of $\sim 1^\circ$ for a burst with fluence 1×10^{-6} erg cm^{-2}. *Daksha* will be able to detect transients on-board, and downlink basic transient information (localization, coarse lightcurves, coarse spectra) within a minute of the trigger. This information will help to trigger the observation of the fast fading afterglow with other different instruments. As mentioned earlier, polarization from GRB emission is one of the important tools to probe the emission mechanisms in GRBs. The estimated polarization capabilities of *Daksha*, due to the open structure, large collecting area and varied orientation of detectors will make it a formidable tool for measuring hard X-ray polarization. With *Daksha*, we expect to study the time-resolved polarization analysis of a larger sample of GRBs. With all the capabilities of *Daksha*, it will be the most effective survey mission for high-energy transients. With its wide field of view, high sensitivity and polarization capabilities, *Daksha* will play a defining role in the study of EM counterparts to GWs and prompt emission from gamma-ray bursts in the coming decade.

4.3 *Radio observation*

Synchrotron radiation of accelerated electrons in shocks formed between expanding outflows and circum-merger material produces radio emission as GW counterpart in NS mergers (Nakar & Piran 2011; Piran *et al.* 2013). Long-lasting radio merger remnants are also expected. Other than this radio emission of coherent prompt radio pulse from a magnetically driven, relativistic plasma outflow prior to the DNS merger are also expected (Hansen & Lyutikov 2001; Pshirkov & Postnov 2010). The radio luminosity is expected to be brighter by a couple of orders of magnitude than that of a typical radio supernova. In addition to above merger led sGRB jet also produces (Hotokezaka *et al.* 2016) a radio afterglow with a few week timescale, observable for small viewing angle detection and already been detected (Fong *et al.* 2015). The strategy and corresponding simulation for radio counterpart detection from NS mergers following GW and other EM waves has been elaborated in Hotokezaka *et al.* (2016).

Radio detection is the key to probing the structure of corresponding merger ejecta regardless of the observing geometry and can put constrain on the structure of magnetic fields via polarization measurements. Currently radio telescopes, such as Karl G. Jansky very large array (VLA) are employed in dedicated radio survey for such detection in addition to pulser timing array (PTA) exploration. With their unprecedented sensitivity, high angular resolution and higher survey speed the square kilometer array (SKA) (Dewdney *et al.* 2009) and the next-generation very large array (ngVLA) (McKinnon *et al.* 2019) will be excellent instruments. These will be used for studies and GW counterpart detection from prompt radio bursts produced by ultra-relativistic jets with timescales of weeks to sub-relativistic merger ejecta with timescales of few years (Arimoto *et al.* 2021).

5. Conclusion

CBC events have offered us a unique opportunity to study a wide range of physical and astrophysical processes. One of which has provided us two different views from both GW and EM emissions. Although the era of GW astronomy helped us understand several mysteries of the Universe and narrowing down different theories and model, also left us with several unknowns and few new mysteries. With upcoming observation runs along with the addition of KAGRA and hopefully LIGO-India in later half of this decade, we expect more statistics on GW events and possibly more multi-messenger events as well.

We also expect arrival of new EM survey observatories, namely, Rubin observatory (formerly LSST), Thirty Metre Telescope (TMT) and SKA within this decade to significantly increase the number of BNS and NS–BH merger rates with EM counterparts in LVKIn (LIGO/Virgo/KAGRA/LIGO-India) phase of observation runs. Furthermore, the upcoming proposed missions like *Daksha* will push the sensitivity of EMGW detections. All of this combined will hopefully help us uncover various unanswered questions about the underlying structure and mechanisms of compact objects and high-energy events. We are happy to be in this golden era of astrophysics.

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