Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
Proceedings IAU Symposium No. 363, 2023
E. Troja & M. G. Baring, eds.
doi:10.1017/S1743921322001648

Observations of Gravitational-wave Afterglows

Alessandra Corsi

Department of Physics and Astronomy, Texas Tech University,
Box 1051, Lubbock, TX 79409-1051, USA
email: alessandra.corsi@ttu.edu

Abstract. GW170817, the merger of two neutron stars witnessed through both its gravitational wave siren and its glow at all wavelengths of light, represents the first multi-messenger detection of a compact binary merger. The association of the GW in-spiral signal from GW170817 with a γ-ray burst, a kilonova, and a non-thermal afterglow spanning all bands of the electromagnetic spectrum, has provided rich constraints on the physics and astrophysics of neutron stars. Starting from the example of GW170817, I briefly summarize recent results on observations of electromagnetic afterglows from gravitational wave triggers. In the light of these results, I highlight some key questions that are yet to be answered after the GW170817 discovery. I conclude by commenting briefly on some opportunities that lie in front of us, as improvements in ground-based gravitational wave detectors' sensitivities will transform a trickle of multi-messenger discoveries into a flood, bringing the field of gravitational wave astronomy from its infancy to its maturity.

Keywords. Gravitational waves, radiation mechanisms: general, methods: observational, stars: neutron

1. LIGO, Virgo, and the start of GW astronomy

The discovery of gravitational waves (GWs) and light at all wavelengths from the binary neutron star (NS) merger GW170817 marked the start of a new era in GW astronomy, and it did so in a truly spectacular fashion (LIGO Scientific Collaboration & Virgo Collaboration 2017a). GW170817, which without exaggeration is changing the way we do time-domain astronomy, would not have been uncovered without the Laser Interferometer Gravitational Wave Observatory (LIGO), Virgo, and the many scientists who worked to construct, operate, and analyze the data of these km-scale ground-based GW detectors (Figure 1; Aasi et al. 2015; Acernese et al. 2015).

LIGO and Virgo are Fabry-Perot-Michelson interferometers. In very simple terms and neglecting some not irrelevant details, the functioning of these detectors can be explained as follows. Inside the L-shaped arms, laser light is fired and split via a beam splitter which sends a beam of light into each of the two perpendicular arms of the detector. Mirrors placed at the end of the arms reflect back the light, and the two beams are then recombined in an output photodetector. The effect of GWs traveling through the L-shaped detectors is to stretch one arm while compressing the other, inducing a relative arm length difference $\Delta L/L < 10^{-21}$ (for typical source parameters), which changes the interference pattern of the recombined light collected in the photodetector. Thus, ground-based detectors such as LIGO and Virgo ultimately measure the spacetime strain induced

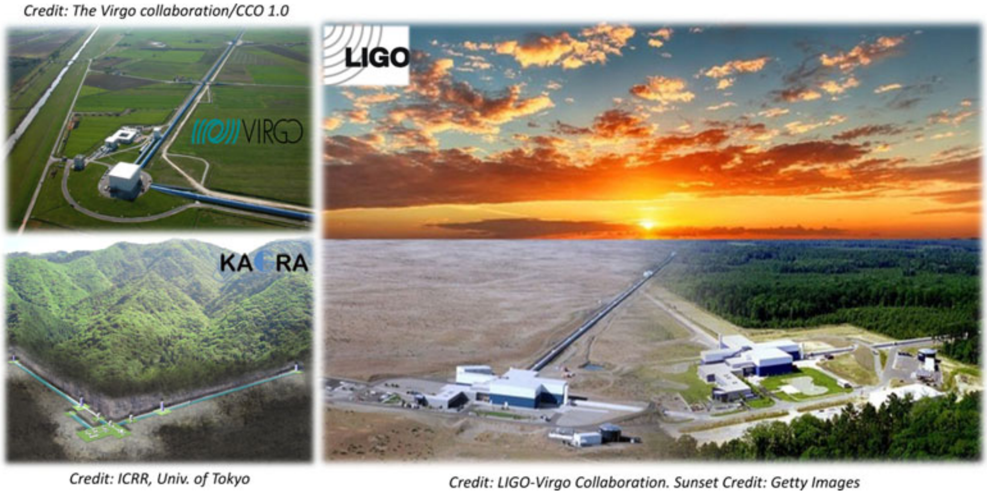

Figure 1. The current network of km-scale ground-based GW detectors. On the top-left is the European 3 km-long arms Virgo detector, located in Italy. On the bottom-left is the Japanese KAGRA detector (also with 3 km-long arms). On the right is a composite image showing the two 4 km-long arms USA detectors of LIGO (the Hanford interferometer is shown to the left; the Livingston interferometer is shown to the right). Image credits: The Virgo collaboration/CCO 1.0; ICRR, Univ. of Tokyo; LIGO-Virgo Collaboration; Getty Images.

by GWs as a time-varying phase difference between the recombined laser light coming from the two perpendicular arms.

GW170817 was detected toward the end of the Advanced LIGO-Virgo so-called second observing run (O2; LIGO Scientific Collaboration & Virgo Collaboration 2017a). It can be said that “time zero” of GW astronomy was set about two years before the detection of GW170817 during Advanced LIGO first observing run (O1), and specifically on 14 September 2015 with the Nobel-prize-winning direct detection of GWs from the merging stellar-mass black-hole (BH) binary GW150914 (LIGO Scientific Collaboration & Virgo Collaboration 2016a). But, GW170817 brought us officially into the realm of multi-messenger GW astronomy, as the first GW-discovered compact binary merger involving matter (i.e. two NSs), and thus associated with a definitive detection of light at all wavelengths (see LIGO Scientific Collaboration et al. 2017a,b,c, and references therein).

2. Current GW detections and near-future prospects

During the Advanced LIGO O1, 49 days of simultaneous observation time in the two LIGO detectors were collected. O1 started on September 12, 2015 and ended on January 19, 2016. This run quickly gifted the community with the first ever direction detection of GWs and, by its end, with the discovery of two highly-significant binary BH mergers. But, no detections or significant candidates were compatible with binary coalescences containing a NS: the component masses of all of the identified compact binary coalescences or candidates were above $5\,M_{\odot}$ (LIGO Scientific Collaboration & Virgo Collaboration 2016a,b,c,d, 2019a; LIGO Scientific Collaboration et al. 2016).

The discovery of GWs from GW170817 was achieved by the LIGO-Virgo detector network just before the end of the O2 run, which started on November 30, 2016 and was completed on August 25, 2017 (for a total of 117 days of simultaneous LIGO-detector observing time). Advanced Virgo joined the O2 run on August 1, 2017, a little over two weeks before the GW170817 discovery. On August 17, 2017, the LIGO-Virgo

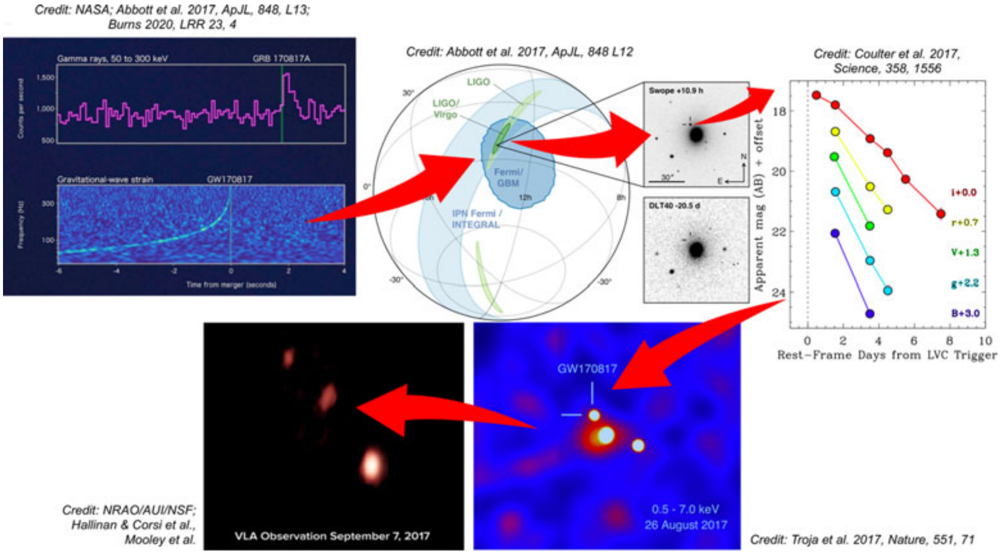

Figure 2. A visual summary of the key sequence of events that brought to the direct detection of GWs and light at all wavelengths from the binary NS merger GW170817. Image credits: NASA; LIGO Scientific Collaboration et al. (2017b); Burns (2020); LIGO Scientific Collaboration et al. (2017a); Troja et al. (2017); NSF; EGO; NASA/Chandra X-ray Observatory; NRAO/AUI/NSF; Hallinan et al. (2017).

detectors observed a GW signal from the in-spiral of two low-mass compact objects consistent with a BNS merger (LIGO Scientific Collaboration & Virgo Collaboration 2017a; LIGO Scientific Collaboration et al. 2017c). GRB 170817 was detected ≈ 1.7 s after the GW merger (Figure 2, top left; see also LIGO Scientific Collaboration et al. 2017b, and references therein). The GW source was rapidly localized to a region of ≈ 31 deg^2 in the sky using data from the LIGO and Virgo detectors alone (Figure 2, center top), and the corresponding skymap was issued to observing partners to allow for follow-up observations. This follow-up effort mobilised a large number of telescopes and observatories on and in orbit around the Earth. The first associated EM signal to be identified was a kilonova dubbed AT 2017gfo (Figure 2, top right; e.g., Chornock et al. 2017; Coulter et al. 2017; Kasliwal et al. 2017; LIGO Scientific Collaboration et al. 2017a; Valenti et al. 2017), an UV/optical/IR quasi-thermal transient whose peak brightness reaches ∼ 1000× that of a classical nova (see also Section 3.1).

The discovery of AT 2017gfo enabled the arcsec localization of GW170817 to a host galaxy (NGC 4993) located ≈ 40 Mpc away (e.g. Blanchard et al. 2017; Coulter et al. 2017). The arcsec localization also enabled monitoring of the GW170817 location with sensitive radio and X-ray telescopes with small fields of view, eventually leading to the discovery of a non-thermal afterglow (e.g. Hallinan et al. 2017; Margutti et al. 2017; Troja et al. 2017, see also Figure 2, bottom center, and Section 3.2).

The detection of an EM counterpart associated with GW170817 spanning from γ-rays to radio, confirmed that at least some BNS mergers are associated with GRBs, and demonstrated the presence of matter in the system, supporting the BNS interpretation derived from considerations based on GW data only (LIGO Scientific Collaboration & Virgo Collaboration 2017a). While the GW and EM data together cannot rule out a BH-NS merger origin for GW170817, the consistency of the GW mass estimates with the masses of known NS in binaries (and their

https://doi.org/10.1017/S1743921322001648 Published online by Cambridge University Press

incompatibility with the masses of known BH in Galactic binary systems) supports the BNS interpretation (LIGO Scientific Collaboration & Virgo Collaboration 2017a).

During the most recent observing run of the LIGO and Virgo detectors (third observing run; O3), a second BNS merger dubbed GW190425 was detected in GWs (LIGO Scientific Collaboration & Virgo Collaboration 2019b). While in terms of its total mass and component masses GW170817 can be defined as a typical BNS, GW190425 is peculiar in the fact that its large total mass of $\approx 3.4\,\mathrm{M}_{\odot}$ makes it a clear outlier when compared with the total mass distribution of known Galactic BNSs (Farrow et al. 2019). Remarkably, a few BH-NS mergers were also unveiled during O3 for the very first time, opening the way to studying a new class of compact binary coalescences (The LIGO Scientific Collaboration et al. 2021b,c). Due to the large sky localizations of the O3 GW detections involving systems with at least one NS (and with a non-extreme mass ratios), no additional definitive EM counterparts were unveiled (e.g., Anand et al. 2021; Bhakta et al. 2021; Gourdji et al. 2022; Kasliwal et al. 2020; Paterson et al. 2021). Perhaps the most interesting result of the O3 LIGO-Virgo observing campaign is that the overall distribution of NS masses it probed hints at being broader than what EM observations alone of Galactic binary systems have probed so far (The LIGO Scientific Collaboration et al. 2021a,b).

Over the next 5-10 years, larger statistical samples of multi-messenger discoveries are likely to enable us to better understand the physics behind compact binary coalescences. A key step forward in building a census of BNS mergers, of their progenitor properties, outflows, and EM counterparts, is expected to soon come into reach with the start of the fourth observing run (O4) of the LIGO and Virgo GW detectors (now planned to start toward the end of 2022†). During O4 the prospects for identifying EM counterparts are much better than O3. Due to substantial upgrade of the Virgo detector, three detectors will operate at an average BNS range $\gtrsim 100\,\mathrm{Mpc}$ (Kagra Collaboration et al. 2018), and the events that could be detected only by two detectors during O3 will become three-detector events in O4. The Japanese detector KAGRA (Figure 1, bottom left) will also join the network (though with a sensitivity subject to large uncertainties). With these improvements, we expect an order of magnitude more BNS detections in O4 compared to O3. About 0.5–6 BNSs mergers are expected to have kilonova counterparts detectable with large filed-of-view optical telescopes such as the Zwicky Transient Facility (Bellm et al. 2019; Petrov et al. 2022). It is thus likely to expect that these arcsec-localized kilonovae will enable extensive follow-up at other wavelengths, bringing scientific results as impactful as GW170817 into reach.

3. GW170817: Lessons learned and open questions

After the discovery of GW170817 in GWs, each band of the EM spectrum contributed key follow-up information that has helped the community form an amazingly detailed picture of the complex physics at play in this BNS merger (a non-exhaustive list of important works on this topic includes Alexander et al. 2017; Arcavi et al. 2017; Balasubramanian et al. 2021; Broderick et al. 2020; Chornock et al. 2017; Corsi et al. 2018; Coulter et al. 2017; Cowperthwaite et al. 2017; Dobie et al. 2018; Drout et al. 2017; Fong et al. 2019; Ghirlanda et al. 2019; Goldstein et al. 2017; Haggard et al. 2017; Hajela et al. 2019; Hallinan et al. 2017; Kasen et al. 2017; Kasliwal et al. 2017; Kilpatrick et al. 2017; LIGO Scientific Collaboration et al. 2017a,b; Lyman et al. 2018; Makhathini et al. 2021; Margutti et al. 2017; Mooley et al. 2018a,b,c; Nicholl et al. 2017; Pian et al. 2017; Savchenko et al. 2017; Shappee et al. 2017; Smartt et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; Troja et al. 2017, 2019, 2022;

† https://www.ligo.org/scientists/GWEMalerts.php

https://doi.org/10.1017/S1743921322001648 Published online by Cambridge University Press

Valenti et al. 2017). The incredible wealth of varied probes that GW170817 enjoyed has provided a unique opportunity to learn about NS structure and astrophysics (e.g., Gill & Granot 2020; Hotokezaka et al. 2018; Kasen et al. 2017; Kathirgamaraju et al. 2019; Lazzati et al. 2018; LIGO Scientific Collaboration & Virgo Collaboration 2018, 2019c; LIGO Scientific Collaboration et al. 2017c; Margalit & Piran 2020; Margutti & Chornock 2021; Metzger 2017; Nakar 2020; Nakar et al. 2018; Nedora et al. 2021; Radice et al. 2018). After ≈ 4 years of extensive follow-up observations across different GW timescales (LIGO Scientific Collaboration & Virgo Collaboration 2017a,b, 2019d) and across various frequencies of the EM spectrum (e.g., Balasubramanian et al. 2021; Hajela et al. 2021; Makhathini et al. 2021; Troja et al. 2022), a consensus picture has emerged. This picture shows similarities with previous theoretical predictions, but at the same time leaves some key questions open. Hereafter, I provide a (likely non-fully-comprehensive) summary of what we have learned from GW170817, and what remains a mystery to be clarified, focusing on EM afterglow observations.

3.1. *The GW170817 kilonova (AT 2017gfo): does it have a non-thermal afterglow?*

The material that is unbound during the merger of two NSs is expected to be very neutron-rich, thus a large number of neutrons can rapidly (compared to the β-decay timescale, hence the name r-process) capture on the few heavy nuclides present and produce nuclei of nuclear mass up to 300 (see e.g. Lippuner & Roberts 2015, and references therei). These heavy nuclei eventually decay, and the energy that comes from thermalizing the products of the nuclear decay can power a so-called kilonova.

The detection of AT 2017gfo associated with GW170817 was a key success of the theory of NS astrophysics (see Metzger 2017, and references therein). However, this kilonova also presented some puzzling features that can be summarized saying it was somewhat bluer than expected. More specifically, UV/optical/IR observations of GW170817 showed evidence for an ejecta that expanded and cooled rapidly over the first hour of observations (Shappee et al. 2017). Around ≈ 1.5 d since merger, the spectra showed evidence for broad features and for a distinct blue (early-time) component, and red (late-time) component (Figure 2, top right; see e.g., Coulter et al. 2017; Kasen et al. 2017; Kasliwal et al. 2017; Metzger 2017; Shappee et al. 2017; Valenti et al. 2017).

It is now believed that the different kilonova components observed in GW170817 are related to the existence of ejecta with different properties (for recent reviews see e.g. Kasen et al. 2017; Lippuner & Roberts 2015; Metzger 2017, and references therein). This can be understood as follows. The total mass and velocity of the neutron-rich ejecta, and its composition (which in turn determines the nuclear heating rate and opacity), are key parameters that impact the observed kilonova properties. Specifically, the duration of the kilonova light curve and its characteristic luminosity depend on the mass, velocity, and opacity of the ejecta (see e.g. Equations 2 and 3 in Kasen et al. 2017). Broadly speaking, a larger ejecta mass produces a brighter and longer-lived kilonova; a higher velocity gives rise to a brighter and shorter kilonova; a higher opacity produces a redder kilonova peaking at later times. The opacity is larger for compositions richer in atomic complexity, such as lanthanides and actinides, because it is related to the blending of millions of bound-bound atomic line transitions (Kasen et al. 2017).

The ejecta components that determine the properties of the kilonova as described above are formed during the in-spiral and merger of the BNS (see Table 2 in Metzger 2017, for a nice summary). The dynamical ejecta launched in the equatorial plane and immediately unbound as a result of tidal forces (tidal tails) typically has a high opacity, speeds up to 20%-30% the speed of light c, a small electron fraction, and a lanthanide-rich composition. Most of the tidally disrupted mass remains bound and circularizes into a torus. This torus

https://doi.org/10.1017/S1743921322001648 Published online by Cambridge University Press

provides both a central engine for a relativistic GRB jet, and an additional source of r-process ejecta via slower expanding outflows (a.k.a. disk outflows). The disk outflows can have a broad electron fraction distribution (and hence can contribute to both a red and blue kilonova), that can be enhanced via neutrino irradiation by a NS remnant. Ejecta with lower opacity, higher electron fractions, and light r-process nuclei can also originate from the material that is ejected in the polar direction due to shock heating in the region where the two NS collide (typically referred to as shock-heated dynamical ejecta).

The red, slow-evolving component of the GW170817 kilonova requires about $0.05\,M_\odot$ of lanthanide-rich material. The blue kilonova associated with GW170817 requires about $0.02\,M_\odot$ of material with an electron fraction $Y_e \gtrsim 0.25$ and a speed of $\approx 0.25\,c$ (with c being the speed of light). As discussed in more details in the recent review by Sarin & Lasky (2021), while the observational constraints on the GW170817 kilonova ejecta speed and mass are compatible with numerical simulations, the relatively large amount of ejecta required to power the blue kilonova specifically is inconsistent with an origin related entirely to shock-heated dynamical ejecta, and requires the contribution from disk winds (whose mass is proportional to the mass of the remnant disk). The disk wind contribution is suppressed in BNS systems that result in rapid or prompt BH formation and for which the collapse happens on a timescale shorter than the hydrodynamic processes responsible for the formation of the disk itself. These considerations support the idea that the merger of GW170817 left behind a short-lived NS rather than a promptly formed BH (see also Gill et al. 2019, and references therein).

A key question that remains to be answered going forward is how common are the complex traits observed in the GW170817 kilonova, and how solid is our interpretation of them. Mapping the diversity of possible kilonova outcomes (in terms of their UV/optical/IR properties), and how this diversity links to the ejecta properties, will answer this question. Moreover, with a larger number of kilonova discoveries, we can hope to use the derived constraints on the ejecta to learn about the progenitor systems themselves, and the NS EoS (thus complementing constraints derived using GW observations alone). For example, Nicholl et al. (2021) have discussed how the dynamical ejecta mass depends on the mass ratio of the binary and the compactness of the NSs. The ratio of red to blue kilonova ejecta, instead, is largely determined by the mass ratio of the progenitor BNS system, and largely insensitive to the total mass of the progenitor system or the EoS. The nature of the merger remnant (short-lived, long-lived, or stable NS versus promptly-formed BH) also impacts the blue kilonova component mass. To first order, the longer the remnant lifetime, the larger the mass of the disk with a higher electron fraction. These correlations remain to be explored observationally.

There is also another question which has become rather hot at the time of writing, which pertains whether we can derive additional constraints on the kilonova ejecta, the nature of the merger remnant, and the NS EoS, using observations in bands other than the UV/optical/IR, by searching for a radio-to-X-ray non-thermal kilonova afterglow (e.g., Balasubramanian et al. 2021; Hajela et al. 2021; Troja et al. 2022). Indeed, several theoretical scenarios predict the possible emergence at late times of a kilonova afterglow in the presence of a high-velocity kilonova ejecta tail which cannot be probed using UV/optical/IR observations (e.g., Hotokezaka et al. 2018; Kathirgamaraju et al. 2019; Margalit & Piran 2020; Nakar & Piran 2011).

Tentative evidence for a very late-time re-brightening possibly associated with the kilonova afterglow of GW170817 has been reported in the X-rays (Hajela et al. 2021), but not in the radio (Balasubramanian et al. 2021). The observational follow-up campaign aimed at hunting for the AT 2017gfo radio-to-X-ray afterglow continues as this proceeding is being written. However, observations available so far favor a relatively steep energy-speed distribution where the energy associated with ejecta of a certain

Lorentz factor Γ decreases relatively fast with increasing Γ ($E(>\beta\Gamma) \propto (\beta\Gamma)^{-\alpha}$ with $\alpha \gtrsim 5$; Balasubramanian et al. 2021). Simulations have shown that, for an equal mass ratio BNS, the steeper the energy-velocity distribution, the stiffer the NS EoS for a given cold, non-rotating maximum mass. For EoS with the same stiffness (i.e. with the same radii at NS masses of $1.4\,M_\odot$), the steeper the energy-velocity ejecta distribution, the larger the cold, non-rotating maximum NS mass. Thus, if future radio observations reveal a kilonova afterglow, these trends would favor moderate stiffness and mass ratio models that enable a stronger core bounce compared to stiff EoS and relatively high mass ratio scenarios (Nedora et al. 2021).

3.2. *GW170817 and its non-thermal afterglow from a structured jet (GRB 170817a)*

As discussed in Section 3.1, most of the tidally disrupted mass that is not immediately unbound circularizes into a torus, whose accretion onto the compact merger remnant (either a NS or a BH) can power a relativistic jet (GRB) of total energy proportional to the total accreted mass (Lazzati & Perna 2019, and references therein). As noted in Section 2, γ-rays observed starting 1.7 s after the GW170817 merger confirmed that at least some BNSs power short GRBs (i.e. relativistic jets). However, GRB 170817a was (energetically) a factor of $\sim 10^3$ weaker than ordinary short GRBs (see LIGO Scientific Collaboration et al. 2017b, and references therein). The exact origin of the sub-energetic prompt emission of GRB 170817, as well as the reason for the delayed onset of the γ-ray signal compared to the time of the merger, are still open questions. The reader is referred to the recent review by Lazzati (2020) for a comprehensive discussion of these questions. Hereafter, we focus on the non-thermal afterglow that accompanied GW170817/GRB 170817a.

Thanks to the arcsec localization of GW170817, enabled by the discovery of its associated kilonova (Section 3.1), some of the most sensitive radio and X-ray telescopes were pointed at the location of the merger to search for a broad-band non-thermal afterglow. This observational campaign was motivated by what was previously known about cosmological GRBs: they are followed by a panchromatic afterglow extending from radio to X-rays (note that in the case of GW170817, at early times the optical band is dominated by the kilonova emission; see Figure 2, top right). The afterglow flux in cosmological GRBs typically follows a power-law decay as a function of time (Fong et al. 2015) starting right after the prompt emission. With GW170817, however, a different story unfolded. A delayed synchrotron afterglow from GW170817/GRB 170817a was first observed in the X-rays ≈ 9 days after the merger by the *Chandra* observatory (e.g., Haggard et al. 2017; Margutti et al. 2017; Troja et al. 2017). A radio afterglow detection with the Karl G. Jansky Very Large Array (VLA) followed, about two weeks after the merger (Hallinan et al. 2017). The isotropic-equivalent luminosity was $\approx 3000\times$ less than the median value of on-axis short GRB X-ray afterglows, and $\gtrsim 10^4\times$ less than that for detected short GRB radio afterglows (Fong et al. 2017).

Ultimately, the GRB 170817a unusual observational properties revealed that this GRB, in addition to being the closest short GRB ever detected, was also the first ever structured relativistic jet to be observed off-axis (e.g., Alexander et al. 2017; Fong et al. 2019; Ghirlanda et al. 2019; Hajela et al. 2019; Lazzati et al. 2018; Makhathini et al. 2021; Mooley et al. 2018a,b,c; Troja et al. 2019). Specifically, comparison of the radio-to-X-ray observations with hydrodynamic simulations were able to rule out a uniform energy-velocity (top-hat) ejecta in favour of a structured jet (a.k.a. jet plus cocoon), where the ejecta velocity varies with the angle from the jet axis (Lazzati et al. 2018). Overall, these observations constrained the opening angle of the jet core ($\lesssim 5$ deg), the observer's viewing angle ($\approx 15-30$ deg), the isotropic equivalent energy ($\sim 10^{52}$ erg), and the interstellar medium (ISM) density ($\sim 10^{-4} - 0.5\,\mathrm{cm}^{-3}$).

As underlined by Lazzati (2020), even though the plethora of panchromatic observations made it possible to establish that the non-thermal afterglow of GRB170817a was powered by a successful and structured relativistic jet, the exact structure of such jet remains degenerate and functions ranging from Gaussian, power-law, and exponential all seem to provide adequate fits to the data. Numerical simulation results have been prone to similar ambiguities. This is a major issue because the jet structure impacts critically our expectations for future multi-messenger discoveries of GWs, and it encodes information about the nature of the inner engine that powers the jet. A promising way to make progress in our understanding of astrophysical jets associated with BNS mergers is to aim to characterize the diversity in their intrinsic properties, i.e. the properties those jets have when released by their central engines, and before the interaction with the surrounding material takes place (Lazzati & Perna 2019). This is of course non trivial, because the observational traits of a jet map the outflow properties as molded by the environment in which that outflow has propagated before reaching transparency. However, Lazzati & Perna (2019) have shown that it is possible to link the jet-cocoon structure (and thus the observed properties of the broad-band afterglow) to the BNS ejecta mass, velocity, and time delay between merger and launch of the jet. To first order, a larger ejecta mass correlates with a more energetic but slower cocoon confined in a narrower angle, with a jet head also confined into a narrow angle. In turn, a larger ejecta mass can be mapped onto the properties of the progenitor itself, such as a larger mass asymmetry in the BNS. Indeed, simulations show that larger progenitor mass ratios tend to result in the partial disruption of the smaller star during the merger, producing more massive tidal outflows (but smaller amount of shock-heated material since the stars merge less violently, so the kilonova is expected to be redder). Observationally, the lower Lorentz factor of the cocoon implies a later onset of the radio and X-ray afterglows, while the narrower jet imprints a clearer jet feature at the light-curve peak. On the other hand, very-low-mass ejecta produce a very weak but fast-moving cocoon and wide angle jet, reflected in light curves that peak early and resemble more closely those of canonical, on-axis jets. These correlations need to be explored systematically and put on solid grounds by future multi-messenger discoveries.

It is clear from the above discussion that a continued, extensive EM follow-up effort is going to be needed for each well-localized GW detection to really pin down the physics and astrophysics of BNS and BH-NS mergers. A particularly promising way forward is through a combination of afterglow imaging (Ghirlanda et al. 2019; Mooley et al. 2018b) and polarization measurements (Corsi et al. 2018). Indeed, Gill & Granot (2018) have shown how different physically motivated angular and radial BNS ejecta structures that can all fit the observed GW170817 lightcurves and spectrum, predict a rather different evolution of the afterglow image (size, shape, and flux centroid), and linear polarization. For these more sophisticated observations techniques to become possible and applicable is a systematic fashion, we are likely to need detectors of improved sensitivity and resolution, such as the next generation VLA (see Section 4).

4. Conclusion

Now that the multi-messenger detection of a compact binary coalescence has been achieved with the current generation of advanced km-scale ground-based GW detectors, and by a suite of telescopes across the globe and instruments from space, it is of imperative importance to work toward implementing the necessary improvements in detectors' sensitivity and data analysis techniques required to bring the full potential of GW multi-messenger astronomy into fruition. Starting from 2025 and over the next 5-10 years, LIGO is expected to transition to its A+ configuration (5× the GW event detection rate; Kagra Collaboration et al. 2018). LIGO A+ will likely be followed by third-generation (3G) detectors such as the Cosmic Explorer† (Dwyer et al. 2015; Reitze et al. 2019a,b). The Cosmic Explorer has the potential to transform the current trickle of BNS and BH-NS GW detections into a flood, yielding hundreds of thousands of detections per year of compact binary systems containing at least one NS. 3G GW detectors may also bring into reach GW afterglows (or GWs of $\mathcal{O}(10^2 - 10^3\,\mathrm{s})$ duration) from the post-merger remnants of BNS mergers (see e.g., Coyne et al. 2016; LIGO Scientific Collaboration & Virgo Collaboration 2017b, 2019d; Sarin & Lasky 2021; Sowell et al. 2019, and references therein), whose existence has been proposed to explain features such as X-ray plateaus in short GRB afterglows (e.g., Rowlinson et al. 2013).

The future of multi-messenger time-domain astronomy is thus very promising, especially if EM facilities will progress in tandem with GW ones, extending multi-messenger studies to larger redshifts. Some of the most critical efforts in relation to observations of EM afterglows of GWs include an optimized Rubin LSST follow-up strategy aimed at uncovering kilonovae (e.g., Andreoni et al. 2021, and references therein), the construction of a next generation Very Large Array (ngVLA‡), and the operation of 30 m class telescopes (see e.g. Beasley et al. 2019; Chornock et al. 2019; Corsi et al. 2019). The reader is referred to Table 2.2 in the “The Next Generation Global Gravitational Wave Observatory Science Book” ¶ for a more complete overview of the landscape of current and future EM facilities that could contribute to the discovery of GW afterglows across the EM spectrum.

It is worth mentioning that space-based GW detectors such as LISA (Amaro-Seoane et al. 2017) may also open the way to multi-band, multi-messenger GW astronomy beyond the realm of kilonovae. Indeed, a particularly exciting prospect is the possibility of studying ultra-short-delay-times compact binary coalescences of BNS and BH-NS. These would show GW precursors in LISA, merge in the LIGO band, and have a potential (stripped-envelope) supernova association (see e.g. Michaely & Perets 2018).

Finally, with GW astronomy still in its infancy, it is crucial to recognize that we are yet unveil some of the GW sources that do not belong to the class of compact binary mergers, but that are expected to populate our universe and to constitute the next set of breakthrough discoveries (e.g., Shoemaker et al. 2021).

References

Aasi, J., et al. 2015, *Class. Quant. Grav.*, 32, 074001, doi: 10.1088/0264-9381/32/7/074001

Acernese, F., et al. 2015, *Class. Quant. Grav.*, 32, 024001, doi: 10.1088/0264-9381/32/2/024001

Alexander, K. D., Berger, E., Fong, W., et al. 2017, *Astrophys. J. Lett.*, 848, L21, doi: 10.3847/2041-8213/aa905d

Amaro-Seoane, P., Audley, H., Babak, S., et al. 2017, *arXiv e-prints*, arXiv:1702.00786. https://arxiv.org/abs/1702.00786

Anand, S., Coughlin, M. W., Kasliwal, M. M., et al. 2021, *Nature Astronomy*, 5, 46, doi: 10.1038/s41550-020-1183-3

Andreoni, I., Margutti, R., Sharan Salafia, O., et al. 2021, *arXiv e-prints*, arXiv:2111.01945. https://arxiv.org/abs/2111.01945

Arcavi, I., Hosseinzadeh, G., Howell, D. A., et al. 2017, *Nature (London)*, 551, 64, doi: 10.1038/nature24291

Balasubramanian, A., Corsi, A., Mooley, K. P., et al. 2021, *Astrophys. J. Lett.*, 914, L20, doi: 10.3847/2041-8213/abfd38

Beasley, A., Wolff, S., Dickinson, M., et al. 2019, in Bulletin of the American Astronomical Society, Vol. 51, 88

† https://dcc.cosmicexplorer.org/public/0163/P2100003/007/ce-horizon-study.pdf

‡ https://ngvla.nrao.edu/

¶ https://gwic.ligo.org/3Gsubcomm/docs/GWIC_3G_Science_Book.pdf

https://doi.org/10.1017/S1743921322001648 Published online by Cambridge University Press

Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019, *Pub. of the Astron. Soc. of the Pacific*, 131, 018002, doi: 10.1088/1538-3873/aaecbe
Bhakta, D., Mooley, K. P., Corsi, A., et al. 2021, *Astrophys. J.*, 911, 77, doi: 10.3847/1538-4357/abeaa8
Blanchard, P. K., Berger, E., Fong, W., et al. 2017, *Astrophys. J. Lett.*, 848, L22, doi: 10.3847/2041-8213/aa9055
Broderick, J. W., Shimwell, T. W., Gourdji, K., et al. 2020, *Mon. Not. of the Royal Astron. Soc.*, 494, 5110, doi: 10.1093/mnras/staa950
Burns, E. 2020, *Living Reviews in Relativity*, 23, 4, doi: 10.1007/s41114-020-00028-7
Chornock, R., Berger, E., Kasen, D., et al. 2017, *Astrophys. J. Lett.*, 848, L19, doi: 10.3847/2041-8213/aa905c
Chornock, R., Cowperthwaite, P. S., Margutti, R., et al. 2019, *Bulletin of the American Astronomical Society*, 51, 237. https://arxiv.org/abs/1903.04629
Corsi, A., Hallinan, G. W., Lazzati, D., et al. 2018, *Astrophys. J. Lett.*, 861, L10, doi: 10.3847/2041-8213/aacdfd
Corsi, A., Lloyd-Ronning, N. M., Carbone, D., et al. 2019, *Bulletin of the American Astronomical Society*, 51, 209
Coulter, D. A., Foley, R. J., Kilpatrick, C. D., et al. 2017, *Science*, 358, 1556, doi: 10.1126/science.aap9811
Cowperthwaite, P. S., Berger, E., Villar, V. A., et al. 2017, *Astrophys. J. Lett.*, 848, L17, doi: 10.3847/2041-8213/aa8fc7
Coyne, R., Corsi, A., & Owen, B. J. 2016, *Phys. Rev. D*, 93, 104059, doi: 10.1103/PhysRevD.93.104059
Dobie, D., Kaplan, D. L., Murphy, T., et al. 2018, *The Astrophysical Journal*, 858, L15, doi: 10.3847/2041-8213/aac105
Drout, M. R., Piro, A. L., Shappee, B. J., et al. 2017, *Science*, 358, 1570, doi: 10.1126/science.aaq0049
Dwyer, S., Sigg, D., Ballmer, S. W., et al. 2015, *Phys. Rev. D*, 91, 082001, doi: 10.1103/PhysRevD.91.082001
Farrow, N., Zhu, X.-J., & Thrane, E. 2019, *Astrophys. J.*, 876, 18, doi: 10.3847/1538-4357/ab12e3
Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, *Astrophys. J.*, 815, 102, doi: 10.1088/0004-637X/815/2/102
Fong, W., Berger, E., Blanchard, P. K., et al. 2017, *Astrophys. J. Lett.*, 848, L23, doi: 10.3847/2041-8213/aa9018
Fong, W., Blanchard, P. K., Alexander, K. D., et al. 2019, *Astrophys. J. Lett.*, 883, L1, doi: 10.3847/2041-8213/ab3d9e
Ghirlanda, G., Salafia, O. S., Paragi, Z., et al. 2019, *Science*, 363, 968, doi: 10.1126/science.aau8815
Gill, R., & Granot, J. 2018, *Mon. Not. of the Royal Astron. Soc.*, 478, 4128, doi: 10.1093/mnras/sty1214
Gill, R., & Granot, J. 2020, *Mon. Not. of the Royal Astron. Soc.*, 491, 5815, doi: 10.1093/mnras/stz3340
Gill, R., Nathanail, A., & Rezzolla, L. 2019, *The Astrophysical Journal*, 876, 139, doi: 10.3847/1538-4357/ab16da
Goldstein, A., Veres, P., Burns, E., et al. 2017, *Astrophys. J. Lett.*, 848, L14, doi: 10.3847/2041-8213/aa8f41
Gourdji, K., Rowlinson, A., Wijers, R. A. M. J., et al. 2022, *Mon. Not. of the Royal Astron. Soc.*, 509, 5018, doi: 10.1093/mnras/stab3197
Haggard, D., Nynka, M., Ruan, J. J., et al. 2017, *Astrophys. J. Lett.*, 848, L25, doi: 10.3847/2041-8213/aa8ede
Hajela, A., Margutti, R., Alexander, K. D., et al. 2019, *Astrophys. J. Lett.*, 886, L17, doi: 10.3847/2041-8213/ab5226

Hajela, A., Margutti, R., Bright, J. S., et al. 2021, *arXiv e-prints*, arXiv:2104.02070. https://arxiv.org/abs/2104.02070
Hallinan, G., Corsi, A., Mooley, K. P., et al. 2017, *Science*, 358, 1579, doi: 10.1126/science.aap9855
Hotokezaka, K., Kiuchi, K., Shibata, M., Nakar, E., & Piran, T. 2018, *Astrophys. J.*, 867, 95, doi: 10.3847/1538-4357/aadf92
Kagra Collaboration, LIGO Scientific Collaboration, & Virgo Collaboration. 2018, *Living Reviews in Relativity*, 21, 3, doi: 10.1007/s41114-018-0012-9
Kasen, D., Metzger, B., Barnes, J., Quataert, E., & Ramirez-Ruiz, E. 2017, *Nature (London)*, 551, 80, doi: 10.1038/nature24453
Kasliwal, M. M., Nakar, E., Singer, L. P., et al. 2017, *Science*, 358, 1559, doi: 10.1126/science.aap9455
Kasliwal, M. M., Anand, S., Ahumada, T., et al. 2020, *Astrophys. J.*, 905, 145, doi: 10.3847/1538-4357/abc335
Kathirgamaraju, A., Giannios, D., & Beniamini, P. 2019, *Mon. Not. of the Royal Astron. Soc.*, 487, 3914, doi: 10.1093/mnras/stz1564
Kilpatrick, C. D., Foley, R. J., Kasen, D., et al. 2017, *Science*, 358, 1583, doi: 10.1126/science.aaq0073
Lazzati, D. 2020, *Frontiers in Astronomy and Space Sciences*, 7, 78, doi: 10.3389/fspas.2020.578849
Lazzati, D., & Perna, R. 2019, *Astrophys. J.*, 881, 89, doi: 10.3847/1538-4357/ab2e06
Lazzati, D., Perna, R., Morsony, B. J., et al. 2018, *Phys. Rev. Lett.*, 120, 241103, doi: 10.1103/PhysRevLett.120.241103
LIGO Scientific Collaboration, & Virgo Collaboration. 2016a, *Astrophys. J. Lett.*, 818, L22, doi: 10.3847/2041-8205/818/2/L22
LIGO Scientific Collaboration, & Virgo Collaboration. 2016b, *Phys. Rev. Lett.*, 116, 241103, doi: 10.1103/PhysRevLett.116.241103
LIGO Scientific Collaboration, & Virgo Collaboration. 2016c, *Phys. Rev. Lett.*, 116, 061102, doi: 10.1103/PhysRevLett.116.061102
LIGO Scientific Collaboration, & Virgo Collaboration. 2016d, *The Astrophysical Journal*, 832, L21, doi: 10.3847/2041-8205/832/2/l21
LIGO Scientific Collaboration, & Virgo Collaboration. 2017a, *Phys. Rev. Lett.*, 119, 161101, doi: 10.1103/PhysRevLett.119.161101
LIGO Scientific Collaboration, & Virgo Collaboration. 2017b, *Astrophys. J. Lett.*, 851, L16, doi: 10.3847/2041-8213/aa9a35
LIGO Scientific Collaboration, & Virgo Collaboration. 2018, *Phys. Rev. Lett.*, 121, 161101, doi: 10.1103/PhysRevLett.121.161101
LIGO Scientific Collaboration, & Virgo Collaboration. 2019a, *Physical Review X*, 9, 031040, doi: 10.1103/PhysRevX.9.031040
LIGO Scientific Collaboration, & Virgo Collaboration. 2019b, *Phys. Rev. D*, 99, 104033, doi: 10.1103/PhysRevD.99.104033
LIGO Scientific Collaboration, & Virgo Collaboration. 2019c, *Phys. Rev. X*, 9, 011001, doi: 10.1103/PhysRevX.9.011001
LIGO Scientific Collaboration, & Virgo Collaboration. 2019d, *The Astrophysical Journal*, 875, 160, doi: 10.3847/1538-4357/ab0f3d
LIGO Scientific Collaboration, Virgo Collaboration, et al. 2016, *Astrophys. J. Lett.*, 826, L13, doi: 10.3847/2041-8205/826/1/L13
LIGO Scientific Collaboration, Virgo Collaboration, et al. 2017a, *The Astrophysical Journal*, 848, L12, doi: 10.3847/2041-8213/aa91c9
LIGO Scientific Collaboration, Virgo Collaboration, et al. 2017b, *The Astrophysical Journal*, 848, L13, doi: 10.3847/2041-8213/aa920c
LIGO Scientific Collaboration, Virgo Collaboration, et al. 2017c, *The Astrophysical Journal*, 850, L40, doi: 10.3847/2041-8213/aa93fc

Lippuner, J., & Roberts, L. F. 2015, *The Astrophysical Journal*, 815, 82, doi: 10.1088/0004-637x/815/2/82

Lyman, J. D., Lamb, G. P., Levan, A. J., et al. 2018, *Nature Astronomy*, 2, 751, doi: 10.1038/s41550-018-0511-3

Makhathini, S., Mooley, K. P., Brightman, M., et al. 2021, *Astrophys. J.*, 922, 154, doi: 10.3847/1538-4357/ac1ffc

Margalit, B., & Piran, T. 2020, *Mon. Not. of the Royal Astron. Soc.*, 495, 4981, doi: 10.1093/mnras/staa1486

Margutti, R., & Chornock, R. 2021, *Ann. Rev. A&A.*, 59, 10.1146/annurev-astro-112420-030742

Margutti, R., Berger, E., Fong, W., et al. 2017, *Astrophys. J. Lett.*, 848, L20, doi: 10.3847/2041-8213/aa9057

Metzger, B. D. 2017, *Living Reviews in Relativity*, 20, 3, doi: 10.1007/s41114-017-0006-z

Michaely, E., & Perets, H. B. 2018, *Astrophys. J. Lett.*, 855, L12, 10.3847/2041-8213/aaacfc

Mooley, K. P., Nakar, E., Hotokezaka, K., et al. 2018a, *Nature (London)*, 554, 207, doi: 10.1038/nature25452

Mooley, K. P., Deller, A. T., Gottlieb, O., et al. 2018b, *Nature (London)*, 561, 355, doi: 10.1038/s41586-018-0486-3

Mooley, K. P., Frail, D. A., Dobie, D., et al. 2018c, *Astrophys. J. Lett.*, 868, L11, doi: 10.3847/2041-8213/aaeda7

Nakar, E. 2020, *Phys. Rep.*, 886, 1, doi: 10.1016/j.physrep.2020.08.008

Nakar, E., Gottlieb, O., Piran, T., Kasliwal, M. M., & Hallinan, G. 2018, *Astrophys. J.*, 867, 18, doi: 10.3847/1538-4357/aae205

Nakar, E., & Piran, T. 2011, *Nature (London)*, 478, 82, doi: 10.1038/nature10365

Nedora, V., Radice, D., Bernuzzi, S., et al. 2021, *Mon. Not. of the Royal Astron. Soc.*, 506, 5908, doi: 10.1093/mnras/stab2004

Nicholl, M., Margalit, B., Schmidt, P., et al. 2021, *Mon. Not. of the Royal Astron. Soc.*, 505, 3016, doi: 10.1093/mnras/stab1523

Nicholl, M., Berger, E., Kasen, D., et al. 2017, *Astrophys. J. Lett.*, 848, L18, doi: 10.3847/2041-8213/aa9029

Paterson, K., Lundquist, M. J., Rastinejad, J. C., et al. 2021, *Astrophys. J.*, 912, 128, doi: 10.3847/1538-4357/abeb71

Petrov, P., Singer, L. P., Coughlin, M. W., et al. 2022, *Astrophys. J.*, 924, 54, doi: 10.3847/1538-4357/ac366d

Pian, E., D'Avanzo, P., Benetti, S., et al. 2017, *Nature (London)*, 551, 67, doi: 10.1038/nature24298

Radice, D., Perego, A., Hotokezaka, K., et al. 2018, *Astrophys. J.*, 869, 130, doi: 10.3847/1538-4357/aaf054

Reitze, D., LIGO Laboratory: California Institute of Technology, LIGO Laboratory: Massachusetts Institute of Technology, LIGO Hanford Observatory, & LIGO Livingston Observatory. 2019a, *Bulletin of the American Astronomical Society*, 51, 141. https://arxiv.org/abs/1903.04615

Reitze, D., Adhikari, R. X., Ballmer, S., et al. 2019b, in Bulletin of the American Astronomical Society, Vol. 51, 35. https://arxiv.org/abs/1907.04833

Rowlinson, A., O'Brien, P. T., Metzger, B. D., Tanvir, N. R., & Levan, A. J. 2013, *Mon. Not. of the Royal Astron. Soc.*, 430, 1061, doi: 10.1093/mnras/sts683

Sarin, N., & Lasky, P. D. 2021, *General Relativity and Gravitation*, 53, 59, doi: 10.1007/s10714-021-02831-1

Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017, *Astrophys. J. Lett.*, 848, L15, doi: 10.3847/2041-8213/aa8f94

Shappee, B. J., Simon, J. D., Drout, M. R., et al. 2017, *Science*, 358, 1574, doi: 10.1126/science.aaq0186

Shoemaker, D. H., Ballmer, S., Barsuglia, M., et al. 2021, *arXiv e-prints*, arXiv:2112.12718. https://arxiv.org/abs/2112.12718

Smartt, S. J., Chen, T. W., Jerkstrand, A., et al. 2017, *Nature (London)*, 551, 75, doi: 10.1038/nature24303

Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, *Astrophys. J. Lett.*, 848, L16, doi: 10.3847/2041-8213/aa9059

Sowell, E., Corsi, A., & Coyne, R. 2019, *Phys. Rev. D*, 100, 124041, doi: 10.1103/PhysRevD.100.124041

Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, *Astrophys. J. Lett.*, 848, L27, doi: 10.3847/2041-8213/aa90b6

The LIGO Scientific Collaboration, the Virgo Collaboration, & the KAGRA Collaboration. 2021a, *arXiv e-prints*, arXiv:2111.03634. https://arxiv.org/abs/2111.03634

The LIGO Scientific Collaboration, Virgo Collaboration, & KAGRA Collaboration. 2021b, *arXiv e-prints*, arXiv:2111.03606. https://arxiv.org/abs/2111.03606

The LIGO Scientific Collaboration, Virgo Collaboration, & the KAGRA Collaboration. 2021c, *The Astrophysical Journal Letters*, 915, L5, doi: 10.3847/2041-8213/ac082e

Troja, E., Piro, L., van Eerten, H., et al. 2017, *Nature (London)*, 551, 71, doi: 10.1038/nature24290

Troja, E., van Eerten, H., Ryan, G., et al. 2019, *Mon. Not. of the Royal Astron. Soc.*, 489, 1919, doi: 10.1093/mnras/stz2248

Troja, E., O'Connor, B., Ryan, G., et al. 2022, *Mon. Not. of the Royal Astron. Soc.*, 510, 1902, doi: 10.1093/mnras/stab3533

Valenti, S., David, J. S., Yang, S., et al. 2017, *The Astrophysical Journal*, 848, L24, doi: 10.3847/2041-8213/aa8edf