frontiers
in Astronomy and Space Sciences

REVIEW
published: 25 January 2021
doi: 10.3389/fspas.2020.609460

Mergers of Binary Neutron Star Systems: A Multimessenger Revolution

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On August 17, 2017, less than two years after the direct detection of gravitational radiation from the merger of two ~30 $M_\odot$ black holes, a binary neutron star merger was identified as the source of a gravitational wave signal of ~100 s duration that occurred at less than 50 Mpc from Earth. A short gamma-ray burst was independently identified in the same sky area by the *Fermi* and *INTEGRAL* satellites for high energy astrophysics, which turned out to be associated with the gravitational event. Prompt follow-up observations at all wavelengths led first to the detection of an optical and infrared source located in the spheroidal Galaxy NGC4993 and, with a delay of ~10 days, to the detection of radio and X-ray signals. This article revisits these observations and focusses on the early optical/infrared source, which was thermal in nature and powered by the radioactive decay of the unstable isotopes of elements synthesized via rapid neutron capture during the merger and in the phases immediately following it. The far-reaching consequences of this event for cosmic nucleosynthesis and for the history of heavy elements formation in the Universe are also illustrated.

Keywords: gamma-ray burst, gravitational waves, neutron star, nucleosynthesis, r-process, kilonova

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Specialty section:
This article was submitted to Nuclear Physics, a section of the journal Frontiers in Astronomy and Space Sciences

Received: *23 September 2020*
Accepted: *02 December 2020*
Published: *25 January 2021*

Citation:
Pian E (2021) Mergers of Binary Neutron Star Systems: A Multimessenger Revolution. Front. Astron. Space Sci. 7:609460. doi: 10.3389/fspas.2020.609460

1 INTRODUCTION

Although the birth of "multimessenger" astronomy dates back to the detection of the first solar neutrinos in the 1960s and was rejuvenated by the report of MeV neutrinos from SN 1987A in the Large Magellanic Cloud, the detection of gravitational radiation from the binary neutron star merger on August 17, 2017 (GW170817A), marks the transition to maturity of this approach to observational astrophysics, as it is expected to open an effective window into the study of astrophysical sources which is not limited to exceptionally close (the Sun) or rare (Galactic supernova) events. GW170817 is a textbook case for gravitational physics, because, with its accompanying short gamma-ray burst (GRB) and afterglow and its thermal aftermath "kilonova", it has epitomized the different epiphanies of the coalescence of a binary system of neutron stars and finally allowed us to unify them.

Owing its name to a typical peak luminosity of ~10^{42} erg s^{-1}, i.e., 1000 times larger than that of a typical nova outburst, kilonova is the characteristic optical and infrared source accompanying a binary neutron star merger due to the radioactive decay of the many unstable isotopes of large atomic weight elements synthesized via rapid neutron capture in the promptly formed dynamical ejecta and in the delayed postmerger ejecta. Its evolution, as well as that of the GRB afterglow, was recorded with exquisite detail, thanks to its closeness (40 Mpc). The scope of this article is to review the electromagnetic multiwavelength observations of GW170817 with particular attention to the kilonova phenomenon.

The outline of the review is as follows: **Section 2** sets the context of binary systems of neutrons stars and describes the predicted outcomes of their coalescences; **Section 3** presents the case of GW170817, the only so far confirmed example of double neutron star merger and the multiwavelength features of its electromagnetic counterpart (short GRB and kilonova); **Section 4** focusses on the kilonova, elaborates on its observed optical and near-infrared light curves and spectra, draws the link with nucleosynthesis of heavy elements, and outlines the theoretical framework that is necessary to describe the kilonova properties and implications; **Section 5** summarizes the results and provides an outlook of this line of research in the near future.

2 BINARY NEUTRON STAR MERGERS

Neutron stars are the endpoints of massive stars evolution and therefore ubiquitous in the Universe: on average, they represent about 0.1% of the total stellar content of a Galaxy. Since massive stars are mostly in binary systems (Sana et al., 2012), neutron star binaries should form readily, if the supernova explosion of either progenitor massive star does not disrupt the system (Renzo et al., 2019). Alternatively, binary neutron star systems can form dynamically in dense environments like stellar clusters (see Ye et al., 2020 and references therein). Binary systems composed by a neutron star and a black hole are also viable, but rare (Pfahl et al., 2005), which may account for the fact that none has so far been detected in our Galaxy.

The prototype binary neutron star system in our Galaxy is PSR B1913 + 16, where one member was detected as a pulsar in a radio survey carried out at the Arecibo Observatory (Hulse and Taylor, 1974), and the presence of its companion was inferred from the periodic changes in the observed pulsation period of 59 ms (Hulse and Taylor, 1975). Among various tests of strong general relativity enabled by the radio monitoring of this binary system, which earned the Nobel Prize for Physics to the discoverers in 1993, was the measurement of the shrinking of the binary system orbit, signaled by the secular decrease of the 7.75 h orbital period, that could be entirely attributed to energy loss via gravitational radiation (Taylor and Weisberg, 1982; Weisberg and Huang, 2016 and references therein).

With an orbital decay rate of $\dot{P} = -2.4 \times 10^{-12}$ s s^{-1}, the merging time of the PSR B1913 + 16 system is $\sim$300 Myr. Following the detection of PSR B1913 + 16, another dozen of binary neutron stars systems were detected in our Galaxy (e.g., Wolszczan, 1991; Burgay et al., 2003; Tauris et al., 2017; Martinez et al., 2017). Almost half of these have estimated merging times significantly shorter than a Hubble time. The campaigns conducted by the LIGO interferometers in Sep 2015-Jan 2016 (first observing run) and, together with Virgo, in Nov 2016-Aug 2017 (second observing run), the latter leading to the first detection of gravitational waves from a merging double neutron star system (see **Section 3**), constrained the local merger rate density to be 110–3,840 Gpc^{-3} yr^{-1} (Abbott et al., 2019). This is consistent with previous estimates (see, e.g., Burgay et al., 2003), and, under a series of assumptions, marginally consistent with independent estimates based on double neutron star system formation in the classical binary evolution scenario (Chruslinska et al., 2018). Ye et al. (2020) have estimated that the fraction of merging binary neutron stars that have formed dynamically in globular clusters is negligible. Under the assumption that the event detected by LIGO on April 25, 2019, was produced by a binary neutron star coalescence, the local rate of neutron star mergers would be updated to 250 – 2810 Gpc^{-3} yr^{-1} (Abbott et al., 2020a).

The merger of a binary neutron star system has four predicted outcomes: (1) a gravitational wave signal that is mildly isotropic, with a stronger intensity in the polar direction than in the equatorial plane; (2) a relativistic outflow, which is highly anisotropic and can produce an observable high energy transient; (3) a thermal, radioactive source emitting most of its energy at ultraviolet, optical, and near-infrared wavelengths; and (4) a burst of MeV neutrinos (Eichler et al., 1989; Rosswog and Liebendörfer, 2003) following the formation of the central remnant and possibly of high-energy (>GeV) neutrinos from hadronic interactions within the relativistic jet (Fang and Metzger, 2017; Kimura et al., 2018). While neutrinos are extremely elusive and detectable only from very small distances with present instrumentation (see **Section 5**), the first three observables have been now all detected, as detailed in the next three subsections.

2.1 Gravitational Waves

Coalescing binary systems of degenerate stars and stellar mass black holes are optimal candidates for the generation of gravitational waves detectable from ground-based interferometers as the strong gravity conditions lead to huge velocities and energy losses (Shapiro and Teukolsky, 1983), and the frequency of the emitted gravitational waves reaches several kHz, where the sensitivity of the advanced LIGO, Virgo, and KAGRA interferometers is designed to be maximal (Abbott et al., 2018).

The time behavior of binary systems of compact stars consists of three phases: a first inspiral phase in a close orbit that shrinks as gravitational radiation of frequency proportional to the orbital frequency is emitted, a merger phase where a remnant compact body is produced as a result of the coalescence of the two stars, and a postmerger, or ringdown, phase where the remnant still emits gravitational radiation while settling to its new stable configuration. During the inspiral, the amplitude of the sinusoidal gravitational signal rapidly increases as the distance between the two bodies decreases and the frequency increases (chirp), while in the ringdown phase the signal is an exponentially damped sinusoid. This final phase may encode critical information on the equation of state of the newly formed remnant (a black hole or, in the case of light neutron stars, a massive neutron star or metastable supramassive neutron star). The mathematical tool that is used to describe this evolution is the waveform model that aims at reproducing the dynamics of the system through the application of post-Newtonian corrections of increasing order and at providing the essential parameters that can then be compared with the interferometric observations (Blanchet, 2014; Nakano et al., 2019).

Since the amplitude of gravitational waves depends on the masses of the binary member stars, the signal will be louder and thus detectable from larger distances, for binary systems that involve black holes than those with neutron stars. The current horizon for binary neutron star merger detection with LIGO is ~ 200 Mpc, and 25–30% smaller with Virgo and KAGRA (Abbott et al., 2018). The dependence of the gravitational waves amplitude on the physical parameters of the system implies that gravitational wave sources are standard sirens (Schutz, 1986), provided account is taken of the correlation between the luminosity distance and the inclination of the orbital plane with respect to the line of sight (Nissanke et al., 2010; Abbott et al., 2016).

2.2 Short Gamma-Ray Bursts

GRBs, flashes of radiation of 100–1,000 keV that outshine the entire Universe in this band, have durations between a fraction of a second and hundreds or even thousands of seconds. However, the duration distribution is bimodal, with a peak around 0.2 s (short or subsecond GRBs) and one around 20 s (long GRBs; Kouveliotou et al., 1993). This bimodality is reflected in the spectral hardness, which is on average larger in short GRBs, and in a physical difference between the two groups. While most long GRBs are associated with core-collapse supernovae (Galama et al., 1998; Woosley and Bloom, 2006; Levan et al., 2016), subsecond GRBs are produced by the merger of two neutron stars or a neutron star and a black hole, as long predicted based on circumstantial evidence (Blinnikov et al., 1984; Eichler et al., 1989; Fong et al., 2010; Berger et al., 2013; Tanvir et al., 2013) and then proven by the detection of GW170817 and of its high energy counterpart GRB170817A (**Section 3**). The observed relative ratio of long vs. short GRBs depends on the detector sensitivity and effective energy band (e.g., Burns et al., 2016). However, the duration overlap of the two populations is very large, so that the minimum of the distribution has to be regarded as a rather vaguely defined value (Bromberg et al., 2013).

About 140 short GRBs were localized so far to a precision that is better than 10 arc-minutes[1]; of these, ~100, ~40, and ~10 have a detected afterglow in X-rays, optical, and radio wavelengths, respectively, and ~30 have measured redshifts (these range between $z = 0.111$ and $z = 2.211$, excluding the nearby GRB170817A, see **Section 3.1.1**, and GRB090426, $z = 2.61$, whose identification as a short GRB is not robust, Antonelli et al., 2009). Short GRBs are located at projected distances of a fraction of, to several kiloparsecs from, the centers of their host galaxies, which are of both early and late type, reflecting the long time delay between the formation of the short GRB progenitor binary systems and their mergers (Berger, 2014).

According to the classical fireball model, both prompt event and multiwavelength afterglow of short GRBs are produced in a highly relativistic jet directed at a small angle with respect to the line of sight, whose aperture can be derived from the achromatic steepening (or "jet break") of the observed afterglow light curve (Nakar, 2007). In principle, this could be used to reconstruct the collimation-corrected rate of short GRBs, to be compared with predictions of binary neutron star merger rates. However, these estimates proved to be very uncertain, owing to the difficulty of measuring accurately the jet breaks in short GRB afterglows (Wanajo et al., 2002; Fong et al., 2015; Jin et al., 2018; Lamb et al., 2019; Pandey et al., 2019).

2.3 R-process Nucleosynthesis

Elements heavier than iron cannot form via stellar nucleosynthesis, as no enough neutrons are available for the formation of nuclei and temperatures are not sufficiently high to overcome the repulsive Coulomb barrier that prevents acquisition of further baryons into nuclei (Burbidge et al., 1957). Supernovae (especially the thermonuclear ones) produce large amounts of iron via decay (through ^{56}Co.) of radioactive ^{56}Ni synthesized in the explosion. Heavier nuclei form via four neutron capture processes (Thielemann et al., 2011), the dominant ones being slow and rapid neutron capture, in brief s- and r-process, respectively, where "slow" and "rapid" refer to the timescale of neutron accretion into the nucleus with respect to that of the competing process of β^- decay. In the s-process, neutron captures occur with timescales of hundreds to thousands of years, making β^- decay highly probable, while r-process neutron capture occurs on a timescale of ~0.01 s, leading to acquisition of many neutrons before β^- decay can set on. As a consequence, the s-process produces less unstable, longer-lived isotopes, close to the so-called valley of β-stability (the decay time of a radioactive nucleus correlates inversely with its number of neutrons), while the r-process produces the heaviest, neutron-richest, and most unstable isotopes of heavy nuclei, up to uranium (Sneden et al., 2008; Mennekens and Vanbeveren, 2014; Thielemann et al., 2017; Côté et al., 2018; Horowitz et al., 2019; Kajino et al., 2019; Cowan et al., 2020). Among both s-process and r-process elements, some are particularly stable owing to their larger binding energies per nucleon, which causes their abundances to be relatively higher than others. In the abundances distribution in the solar neighborhood, these are seen as maxima "peaks" centered around atomic numbers $Z = 39$ (Sr-Y-Zr), 57 (Ba-La-Ce-Nd), and 82 (Pb) for the s-process and, correspondingly somewhat lower atomic numbers $Z = 35$ (Se-Br-Kr), 53 (Te-I-Xe), and 78 (Ir-Pt-Au) for the r-process (e.g., Cowan et al., 2020).

Both s-process and r-process naturally occur in environments that are adequately supplied with large neutron fluxes. For the s-process, these are eminently asymptotic giant branch stars, where neutron captures are driven by the ^{13}C (α, n)^{16}O and ^{22}Ne (α, n)^{25}Mg reactions (Busso et al., 1999). The r-process requires much higher energy and neutron densities, which are only realized in most physically extreme environments. While it can be excluded that big-bang nucleosynthesis can accommodate heavy elements formation in any significant amount (Rauscher et al., 1994), there is currently no consensus on the relative amounts of nucleosynthetic yields in the prime r-process candidate sites: core-collapse supernovae and mergers of binary systems composed by neutron stars or a neutron star and a black hole.

[1]http://www.mpe.mpg.de/jcg/grbgen.html

Core-collapse supernovae have been proposed starting many decades ago as sites of r-process nucleosynthesis through various mechanisms and in different parts of the explosion, including dynamical ejecta of prompt explosions of O-Ne-Mg cores (Hillebrandt et al., 1976; Wheeler et al., 1998; Wanajo et al., 2002); C + O layer of O-Ne-Mg-core supernovae (Ning et al., 2007); He-shell exposed to intense neutrino flux (Epstein et al., 1988; Banerjee et al., 2011); re-ejection of fallback material (Fryer et al., 2006); neutrino-driven wind from protoneutron stars (Takahashi et al., 1994; Woosley et al., 1994); and magnetohydrodynamic jets of rare core-collapse SNe (Nishimura et al., 2006; Winteler et al., 2012). Similarly old is the first proposal that the tidal disruption of neutron stars by black holes in close binaries (Lattimer and Schramm, 1974, 1976; Symbalisty and Schramm, 1982; Davies et al., 1994) and coalescences of binary neutron star systems (Eichler et al., 1989) could be at the origin of r-process nucleosynthesis. This should manifest as a thermal optical-infrared source of radioactive nature of much lower luminosity (a factor of 1,000) and shorter duration (rise time of a few days) than supernova (Li & Paczyński, 1998).

The models for r-process elements production in core-collapse supernova all have problems inherent in their physics (mostly related to energy budget and neutron flux density). On the other hand, the binary compact star merger origin may fail to explain observed r-process element abundances in very low metallicities stars, i.e., at very early cosmological epochs, owing to the nonnegligible binary evolution times (see Cowan et al., 2020 for an accurate review of all arguments in favor and against either channel). While the event of August 17, 2017 (**Section 3**), has now provided incontrovertible evidence that binary neutron star mergers host r-process nucleosynthesis, the role of core-collapse supernovae cannot be dismissed although their relative contribution with respect to the binary compact star channel must be assessed (Ramirez-Ruiz et al., 2015; Ji et al., 2016; Shibagaki et al., 2016; Côté et al., 2019; Safarzadeh et al., 2019; Simonetti et al., 2019). It cannot be excluded that both "weak" and "strong" r-process nucleosyntheses take place, with the former occurring mainly in supernova and possibly failing to produce atoms up to the third peak of r-process elemental abundance distribution (Cowan et al., 2020). The hint that heavy elements may be produced in low-rate events with high yields (Sneden et al., 2008; Wallner et al., 2015; Macias and Ramirez-Ruiz, 2019) points to binary compact star mergers or very energetic (i.e., expansion velocities larger than 20,000 km s^{-1}) core-collapse supernovae as progenitors, rather than regular core-collapse supernovae. Along these lines, it has been proposed that accretion disks of collapsars (the powerful core-collapse supernovae that accompany long GRBs, Woosley and Bloom, 2006) produce neutron-rich outflows that synthesize heavy r-process nuclei (Nakamura et al., 2013; Kajino et al., 2014; Nakamura et al., 2015). Siegel et al. (2019) calculated that collapsars may supply more than 80% of the r-process content and computed synthetic spectra for models of r-process-enriched supernovae corresponding to an MHD supernova and a collapsar disk outflow scenario.

Neutrons are tightly packed together in neutrons stars, but during coalescence of a binary neutron star system the tidal forces disrupt them and the released material forms promptly a disk-like rotating structure (dynamical ejecta, Rosswog et al., 1999; Shibata and Hotokezaka, 2019) where the neutron density rapidly drops to optimal values for r-process occurrence ($\sim 10^{24-32}$ neutrons cm^{-3}, Freiburghaus et al., 1999) and for copious formation of neutron-rich stable and unstable isotopes of large atomic number elements (Fernández and Metzger, 2016; Tanaka, 2016; Tanaka et al., 2018; Wollaeger et al., 2018; Metzger, 2019).

3 THE BINARY NEUTRON STAR MERGER OF 17 AUGUST, 2017

On August 17, 2017, the LIGO and Virgo interferometers detected for the first time a gravitational signal that corresponds to the final inspiral and coalescence of a binary neutron star system (Abbott et al., 2017a). The sky uncertainty area associated with the event was 28 square degrees, in principle too large for a uniform search for an electromagnetic counterpart with ground-based and orbiting telescopes. However, its small distance (40^{+8}_{-14} Mpc), estimated via the "standard siren" property of gravitational wave signals associated with binary neutron star mergers, suggested that the aftermath could be rather bright and motivated a large-scale campaign at all wavelengths from radio to very high energy gamma-rays, which was promptly and largely rewarded by success and then timely followed by a long and intensive monitoring (Abbott et al., 2017b; Abbott et al., 2017c), as described in **Section 3.1**. Searches of MeV-to-EeV neutrinos directionally coincident with the source using data from the Super-Kamiokande, ANTARES, IceCube, and Pierre Auger Observatories between 500 s before and 14 days after the merger returned no detections (Albert et al., 2017; Abe et al., 2018).

Based on the detection of electromagnetic radiation, Bauswein et al. (2017) have argued that the merger remnant may not be a black hole or at least the postmerger collapse to a black hole may be delayed. Since the postmerger phase "ring-down" signal of GW170817 was not detected (Abbott et al., 2017e), this hypothesis cannot be tested directly with gravitational data. Bauswein et al. (2017) also derived lower limits on the radii of the neutron stars.

Notably, while the gravitational data made it possible to set an upper limit on the tidal-deformability parameter of the binary neutron stars ($\tilde{\Lambda} \lesssim 800$, Abbott et al., 2017a), the optical observation of kilonova ejecta limited the same parameter from below ($\tilde{\Lambda} \gtrsim 400$, Radice et al., 2018), based on the consideration that for smaller values of $\tilde{\Lambda}$ a long-lived remnant would not be favored, contradicting the result of Bauswein et al. (2017). The limits on the $\tilde{\Lambda}$ parameter constrain the neutron star radius to the range 11.8 km $\lesssim R_{1.5} \lesssim$ 13.1 km, where $R_{1.5}$ refers to a 1.5 $M_\odot$ neutron star (Burgio et al., 2018), and in turn confine the possible ensemble of viable equations of state (Annala et al., 2018; Lim and Holt, 2018), a fundamental, yet poorly known, descriptor of neutron star physics (Özel and Freire, 2016). Furthermore, by circumscribing the number of equations of state of the compact stars, their exploration can be brought beyond nucleonic matter and extended to scenarios of matter presenting a phase transition

(Burgio et al., 2018; Most et al., 2018). The results on the tidal deformability of the neutron star progenitors of GW170817 and on the behavior of the remnant thus provide a brilliant confirmation of the added value of a multimessenger approach over separate observations of individual carriers of information.

3.1 The Electromagnetic Counterpart of GW170817

Independent of LIGO-Virgo detection of the gravitational wave signal, the Gamma-ray Burst Monitor (GBM) onboard the NASA *Fermi* satellite and the Anticoincidence Shield for the gamma-ray Spectrometer (SPI) of the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) satellite were triggered by a faint short GRB (duration of ~ 2 s), named GRB170817A (Abbott et al., 2017b; Goldstein et al., 2017; Savchenko et al., 2017). This gamma-ray transient, whose large error box was compatible with that determined by LIGO-Virgo, lags the gravitational merger by 1.7 s, a delay that may be dominated by the propagation time of the jet to the gamma-ray production site (Beniamini et al., 2020; see however Salafia et al., 2018). The preliminary estimate of the source distance provided a crucial constraint on the maximum distance of the Galaxy that could plausibly have hosted the merger, so that the searching strategy was based on targeting galaxies within a ~ 50 Mpc cosmic volume (see, e.g., Gehrels et al., 2016) with telescopes equipped with large (i.e., several square degrees) field-of-view cameras.

About 70 ground-based optical telescopes participated in the hunt and each of them adopted a different pointing sequence. This systematic approach enabled many groups to identify the optical counterpart candidate in a timely manner (with optical magnitude $V \simeq 17$), i.e., within ~ 12 h of the merger (Arcavi et al., 2017; Lipunov et al., 2017; Soares-Santos et al., 2017; Valenti et al., 2017; Tominaga et al., 2018). Coulter et al. (2017) were the first to report a detection with the optical 1 m telescope Swope at Las Campanas Observatory. The optical source lies at 10 arc-seconds angular separation, corresponding to a projected distance of ~ 2 kpc, from the center of the spheroidal Galaxy NGC 4993 at 40 Mpc (Blanchard et al., 2017; Im et al., 2017; Levan et al., 2017; Pan et al., 2017; Tanvir et al., 2017).

Rapid follow-up of the gravitational wave and GRB signal in X-rays did not show any source comparable to, or brighter than, a typical afterglow of a short GRB. Since both the gravitational data and the faintness of the prompt GRB emission suggested a jet viewed significantly off axis, this could be expected, as the afterglows from misaligned GRB jets have longer rise times than those of jets observed at small viewing angles (Van Eerten and MacFadyen, 2011). Therefore, X-ray monitoring with *Swift*/XRT, *Chandra,* and *Nustar* continued, and ~ 10 days after merger led to the detection with *Chandra* of a faint source ($L_X \simeq 10^{40}$ erg s^{-1}) (Evans et al., 2017; Margutti et al., 2017; Troja et al., 2017), whose intensity continued to rise up to ~ 100 days (D'Avanzo et al., 2018; Troja et al., 2020). Similarly, observations of cm and mm wavelengths at various arrays, including VLA and ALMA, failed to detect the source before ~ 16 days after the gravitational signal, which was interpreted as evidence that a jetted source accompanying the binary neutron star merger must be directed at a significant angle ($\geq 20°$) with respect to the line of sight (Alexander et al., 2017; Andreoni et al., 2017; Hallinan et al., 2017; Kim et al., 2017; Pozanenko et al., 2018).

The *Fermi* Large Area Telescope covered the sky region of GW170817 starting only 20 min after the merger and did not detect any emission in the energy range 0.1–1 GeV to a limiting flux of 4.5×10^{-10} erg s^{-1} cm^{-2} in the interval 1,153–2027 s after the merger (Ajello et al., 2018). Follow-up observation with the atmospheric Cherenkov experiment H.E.S.S. (0.3–8 TeV) from a few hours to ~ 5 days after merger returned no detection to a limit of a few 10^{-12} erg s^{-1} cm^{-2} (Abdalla et al., 2017). A summary of the results of the multiwavelength observing campaign within the first month of gravitational wave signal detection is reported in Abbott et al. (2017c).

While the radio and X-ray detections are attributed to the afterglow of the short GRB, the ultraviolet, optical, and near-infrared data are dominated by the kilonova at early epochs (with a possible contribution at $\lesssim 4$ days at blue wavelengths from cooling of shock-heated material around the neutron star merger, Piro and Kollmeier, 2018) and later on by the afterglow, as described in the next two sections.

3.1.1 The Gamma-Ray Burst and Its Multiwavelength Afterglow

The short GRB170817A, with an energy output of $\sim 10^{46}$ erg, was orders of magnitude dimmer than most short GRBs (Berger, 2014). Together with a viewing angle of ~ 30 deg estimated from the gravitational wave signal (Abbott et al., 2017a), this led to the hypothesis that the GRB was produced by a relativistic jet viewed at a comparable angle. However, the early light curve of the radio afterglow is not consistent with the behavior predicted for an off-axis collimated jet and rather suggests a quasispherical geometry, possibly with two components, a more collimated one and a nearly isotropic and mildly relativistic one, which is responsible also for producing the gamma-rays (Mooley et al., 2018a). This confirms numerous predictions whereby the shocked cloud surrounding a binary neutron star merger forms a mildly relativistic cocoon that carries an energy comparable to that of the jet and is responsible for the prompt emission and the early multiwavelength afterglow (Lazzati et al., 2017a; Lazzati et al., 2017b; Nakar and Piran, 2017; Bromberg et al., 2018; Xie et al., 2018) and is supported by detailed numerical simulations (Gottlieb et al., 2018; Lazzati et al., 2018).

Using milliarcsecond resolution radio VLBI observations at 75 and 230 days, Mooley et al. (2018b) detected superluminal motion with $\beta = 3-5$, while Ghirlanda et al. (2019) determined that, at 207 days, the source is still angularly smaller than two milliarcseconds at the 90% confidence, which excludes that a nearly isotropic, mildly relativistic outflow is responsible for the radio emission, as in this case the source apparent size, after more than six months of expansion, should be significantly larger and resolved by the VLBI observation. These observations point to a structured jet as the source of GRB170817A, with a narrow opening angle ($\theta_{op} \simeq 3.4$ degrees) and an energetic core ($\sim 3 \times 10^{52}$ erg) seen under a viewing angle of $\sim 15°$ (Ghirlanda et al., 2019). This is further confirmed by later radio observations, extending up to 300 days after merger, that show a sharp downturn of the radio light curve, suggestive of a jet rather than a spherical source (Mooley et al., 2018c).

The optical/near-infrared kilonova component subsided rapidly (see **Section 3.1.2**) leaving room to the afterglow emission: the HST observations at ~100 days after the explosion show a much brighter source than inferred from the extrapolation of the early kilonova curve to that epoch (Lyman et al., 2018). This late-epoch flux is thus not consistent with kilonova emission and is rather due to the afterglow produced within an off-axis structured jet (Fong et al., 2019). At X-ray energies, the GRB counterpart is still detected with *Chandra* three years after explosion (Troja et al., 2020), but its decay is not fully compatible with a structured jet, indicating that the physical conditions have changed or that an extra component is possibly emerging (e.g., a nonthermal aftermath of the kilonova ejecta; see next section).

3.1.2 The Kilonova

The early ground-based optical and near-infrared and space-based (with *Swift*/UVOT) near-ultraviolet follow-up observations started immediately after identification of the optical counterpart of GW170817, detecting a rapid rise (~1 day timescale, Arcavi et al., 2017) and wavelength-dependent time decay, quicker at shorter wavelengths (Andreoni et al., 2017; Cowperthwaite et al., 2017; Díaz et al., 2017; Drout et al., 2017; Evans et al., 2017; McCully et al., 2017; Nicholl et al., 2017; Tanvir et al., 2017; Utsumi et al., 2017; Villar et al., 2017). The optical light is polarized at the very low level of (0.50 ± 0.07)% at 1.46 days, consistent with intrinsically unpolarized emission scattered by Galactic dust, indicating that no significant alignment effect in the emission or geometric preferential direction is present in the source at this epoch, consistent with expectation for kilonova emission (Covino et al., 2017).

Starting the same night when the optical counterpart was detected, low resolution spectroscopy was carried out at the Magellan telescope (Shappee et al., 2017). This spectrum shows that the source is not yet transparent as it is emitting black body radiation, whose maximum lies however blueward of the sampled wavelength range, suggesting that the initial temperature may have been larger than ~10,000 K. The following night (1.5 days after merger) the spectrum is still described by an almost perfect black body law whose maximum at ~5000 K was fully resolved by spectroscopy at the Very Large Telescope (VLT) with the X-Shooter spectrograph over the wavelength range 3,500–24,000 Å (Pian et al., 2017). At this epoch, the expansion velocity of the expelled ejecta, whose total mass was estimated to be 0.02–0.05 $M_\odot$ (Pian et al., 2017; Smartt et al., 2017; Waxman et al., 2018), was ~20% of the light speed, which is only mildly relativistic and therefore much less extreme than the ultrarelativistic kinematic regime of the GRB and of its early afterglow, analogous to the observed difference between the afterglows and the supernovae accompanying long GRBs. At 2.5 days after merger, the spectrum starts deviating from a black body as the ejecta become increasingly transparent and absorption lines are being imprinted on the spectral continuum by the atomic species present in the ejecta (Chornock et al., 2017; Pian et al., 2017; Smartt et al., 2017). In the following days these features become prominent and they evolve as the ejecta decelerate and the photosphere recedes (**Figure 1**).

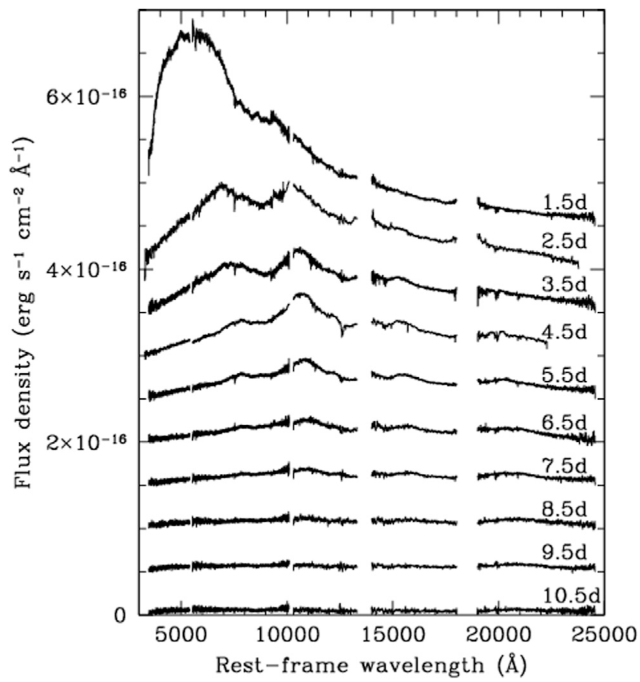

FIGURE 1 | ESO VLT X-Shooter spectra of the counterpart of GW170817 from Pian et al. (2017) and Smartt et al. (2017), at phases indicated in days after merger time, corrected for Galactic extinction E (B-V) = 0.1 mag, deredshifted, and offset in flux by multiples of a 5×10^{-17} erg s^{-1} cm^{-2} $Å^{-1}$ additive constant with respect to the 10.5-day spectrum. Wavelength ranges of poor atmospheric transmission were blanked out. The spectra of the 19th (2.5 days) and the 21st (4.5 days) of August 2017 have been recalibrated with respect to the originally published version, courtesy of J. Gillanders, J. Selsing, and S. Smartt.

In particular, in the spectrum at day 1.5 an absorption feature extending from ~7,000 to ~8,100 Å is detected, so that Smartt et al. (2017) preliminarily identified atomic transitions occurring in neutral Cs and Te, broadened and blueshifted by ~0.2*c*, consistent with the expansion velocity of the photosphere. In the second spectrum (2.5 days) the Cs I and Te I lines are still detected at somewhat larger wavelengths, compatibly with a reduced photospheric expansion speed. These lines were however later disproved on account of the fact that, at the temperature of the ejecta immediately below the photosphere (~3700 K), numerous transitions of other lanthanide elements of higher ionization potential should be observed besides Cs and Te, but are not (Watson et al., 2019). Watson et al. (2019) reanalyzed the absorption feature observed at 7,000–8,100 Å and an absorption feature at ~3,500 Å with the aid of local thermodynamic equilibrium models with abundances from a solar-scaled r-process and from metal-poor stars and determined that the absorption features can be identified with Sr II. In the spectra at the successive epochs the line at the longer wavelength is still detected and develops a P Cygni profile.

Strontium is a very abundant element and is produced close to the first r-process peak. Its possible detection makes it important to consider lighter r-process elements in addition to the lanthanides in shaping the kilonova emission spectrum (Watson et al., 2019).

At $\sim$10 days after merger, the kilonova spectrum fades out of the reach of the largest telescopes. The radioactive source could still be monitored photometrically for another week in optical and near-infrared (Cowperthwaite et al., 2017; Drout et al., 2017; Kasliwal et al., 2017; Pian et al., 2017; Smartt et al., 2017; Tanvir et al., 2017); it was last detected at 4.5 μm with the *Spitzer* satellite 74 days after merger (Villar et al., 2018). The kilonova ejecta are also expected to interact with the circum-binary medium and produce low-level radio and X-ray emission that peaks years after the merger (Kathirgamaraju et al., 2019). The search for this component has not returned (yet) a detection at radio wavelengths (Hajela et al., 2019), but it may start to be revealed at X-rays (Troja et al., 2020).

3.1.3 The Host Galaxy of GW170817

HST and *Chandra* images, combined with VLT MUSE integral field spectroscopy of the optical counterpart of GW170817, show that its host Galaxy, NGC 4993, is a lenticular (S0) Galaxy at z = 0.009783 that has undergone a recent ($\sim$1 Gyr) galactic merger (Levan et al., 2017; Palmese et al., 2017). This merger may be responsible for igniting weak nuclear activity. No globular or young stellar cluster is detected at the location of GW170817, with a limit of a few thousand solar masses for any young system. The population in the vicinity is predominantly old and the extinction from local interstellar medium is low. Based on these data, the distance of NGC4993 was determined to be 41.0 ± 3.1 Mpc (Hjorth et al., 2017). The HST imaging made it also possible to establish the distance of NGC4993 through the surface brightness fluctuation method with an uncertainty of $\sim$ 6% (40.7 ± 1.4 ± 1.9 Mpc, random and systematic errors, respectively), making it the most precise distance measurement for this Galaxy (Cantiello et al., 2018). Combining this with the recession velocity measured from optical spectroscopy of the Galaxy, corrected for peculiar motions, returns a Hubble constant $H_0 = 71.9 \pm 7.1$ km s^{-1} Mpc^{-1}.

Based only on the gravitational data and the standard siren argument and assuming that the optical counterpart represents the true sky location of the gravitational-wave source instead of marginalizing over a range of potential sky locations, Abbott et al. (2017d) determined a "gravitational" distance of $43.8^{+2.9}_{-6.9}$ Mpc that is refined with respect to the one previously reported in Abbott et al. (2017a). Together with the corrected recession velocity of NGC4993, this yields a Hubble constant $H_0 = 70^{+12}_{-8}$ km s^{-1} Mpc^{-1}, comparable to, but less precise than, that obtained from the superluminal motion of the radio counterpart core, H_0 = $70.3^{+5.3}_{-5.0}$ km s^{-1} Mpc^{-1} (Hotokezaka et al., 2019).

4 KILONOVA LIGHT CURVE AND SPECTRUM

The unstable isotopes formed during coalescence of a binary neutron star system decay radioactively and the emitted gamma-ray photons are downscattered to the ultraviolet, optical, and infrared thermal radiation that constitutes the kilonova source (**Section 3.1.2**). Its time decline is determined by the convolution of radioactive decay chain curves of all present unstable nuclei. This is analogous to the supernova phenomenon, where however the vastly dominant radioactive chain is ^{56}Ni decaying into ^{56}Co. and then into ^{56}Fe.

While radioactive nuclei decay, atoms recombine, as the source is cooling, and absorption features are imprinted in the kilonova spectra. Among neutron-rich nuclei, the lanthanides (atomic numbers 57–71) series have full f-shells and therefore numerous atomic transitions that suppress the spectrum at shorter wavelengths ($\lesssim$ 8,000 Å). Spectra of dynamical ejecta of kilonova may therefore be heavily intrinsically reddened, depending on the relative abundance of lanthanides (Barnes and Kasen, 2013; Kasen et al., 2013; Tanaka and Hotokezaka, 2013). Prior to the clear detection of kilonova accompanying GW170817 (**Section 3**), such a source may have been detected in HST images in near-infrared H band of the afterglow of GRB130603B (Berger et al., 2013; Tanvir et al., 2013). Successive claims for association with short GRBs and kilonova radiation were similarly uncertain (Jin et al., 2015; Jin et al., 2016).

If the neutron stars coalescence does not produce instantaneously a black hole and a hypermassive neutron star is formed as a transitory remnant, a neutrino wind is emitted that may inhibit the formation of neutrons and reduce the amount of neutron-rich elements (Fernández and Metzger, 2013; Kajino et al., 2014; Kiuchi et al., 2014; Metzger and Fernández, 2014; Perego et al., 2014; Kasen et al., 2015; Lippuner et al., 2017). This "postmerger" kilonova component, of preferentially polar direction, is thus relatively poor in lanthanides and gives rise to a less reddened spectrum (Kasen et al., 2017; Tanaka et al., 2017).

The optical/near-infrared spectral behavior of kilonova is analogous to that of supernovae with the largest kinetic energies ($>10^{52}$ erg), like those associated with GRBs: the large photospheric velocities broaden the absorption lines and blueshift them in the direction of the observer. Furthermore, broadening causes the lines to blend, which makes it difficult to isolate and identify individual atomic species (Iwamoto et al., 1998; Mazzali et al., 2000; Nakamura et al., 2001). While these effects can be controlled and deconvolved with the aid of a radiation transport model as it has been done for supernovae of all types (Mazzali et al., 2016; Hoeflich et al., 2017; Ergon et al., 2018; Hillier and Dessart, 2019; Ashall and Mazzali, 2020; Shingles et al., 2020), a more fundamental hurdle in modeling kilonova spectra consists in the much larger number of electronic transitions occurring in r-process element atoms than in the lighter ones that populate supernova ejecta, and in our extremely limited knowledge of individual atomic opacities of these neutron-rich elements, owing to the lack of suitable atomic data. First systematic atomic structure calculations for lanthanides and for all r-process elements were presented by Fontes et al. (2020) and Tanaka et al. (2020), respectively.

5 SUMMARY AND FUTURE PROSPECTS

The gravitational and electromagnetic event of August 17, 2017, provided the long-awaited confirmation that binary neutron star mergers are responsible for well identifiable gravitational signals at kHz frequencies, for short GRBs, and for thermal sources, a. k.a. kilonovae or macronovae, produced by the radioactive decay of unstable heavy elements synthesized via r-process during the coalescence. The intensive and long-term electromagnetic monitoring from ground and space allowed clear detection of the counterpart at all wavelengths. Brief (~2 s) gamma-ray emission, peaking at ~200 keV and lagging the gravitational signal by 1.7 s, is consistent with a weak short GRB. At ultraviolet-to-near-infrared wavelengths, the kilonova component—never before detected to this level of accuracy and robustness—dominates during the first 10 days and decays rapidly under detection threshold thereafter, while an afterglow component emerges around day ~100. Up to the most recent epochs of observation (day ~1,000 at X-rays), the kilonova does not add significantly to the bright radio and X-ray afterglow component. Multiepoch VLBI observations measured—for the first time in a GRB—superluminal motion of the radio source, thus providing evidence of late-epoch emergence of a collimated off-axis relativistic jet.

Doubtlessly, this series of breakthroughs were made possible by the closeness of the source (40 Mpc), almost unprecedented for GRBs, and by the availability of first-class ground-based and space-borne instruments. The many findings and exceptional new physical insight afforded by GW170817/GRB170817A make it a *rosetta stone* for future similar events. When a sizable group of sources with good gravitational and electromagnetic detections will be available, the properties of binary systems containing at least one neutron star, of their mergers and their aftermaths, can be mapped. It will then become possible to clarify how the dynamically ejected mass depends on the binary system parameters, mass asymmetry, and neutron stars equation of state (Ruffert and Janka, 2001; Hotokezaka et al., 2013), how the jet forms and evolves, which kinematic regimes and geometry it takes up in time, and how the GRB and afterglow observed phenomenologies can help distinguish the intrinsic properties from viewing angle effects (Janka et al., 2006; Lamb and Kobayashi, 2018; Ioka and Nakamura, 2019), what the detailed chemical content of kilonova ejecta is and how the r-process abundance pattern inferred from kilonova spectra compares with the history of heavy elements cosmic enrichment (Rosswog et al., 2018), how kilonovae can help constrain the binary neutron star rates and how the parent population of short GRBs evolves (Guetta and Stella, 2009; Yang et al., 2017; Belczynski et al., 2018; Artale et al., 2019; Matsumoto and Piran, 2020), and how gravitational and electromagnetic data can be used jointly to determine the cosmological parameters (Schutz, 1986; Del Pozzo, 2012; Abbott et al., 2017d), to mention only some fundamental open problems. Comparison of the optical and near-infrared light curves of GW170817 kilonova with those of short GRBs with known redshift suggests infact significant diversity in the kilonova component luminosities (Gompertz et al., 2018; Rossi et al., 2020).

Regrettably, short GRBs viewed at random angles, and not pole on, are relativistically beamed away from the observer direction and kilonovae are intrinsically weak. These circumstances make electromagnetic detections very difficult if the sources lie at more than ~100 Mpc, as proven during the third and latest observing run (Apr 2019–Mar 2020) of the gravitational interferometers network. In this observing period, two merger events possibly involving neutron stars were reported by the LIGO-Virgo consortium: GW190425, caused by the coalescence of two compact objects of masses each in the range 1.12–2.52 $M_\odot$, at ~160 Mpc (Abbott et al., 2020a), and GW190814, caused by a 23 $M_\odot$ black hole merging with a compact object of 2.6 $M_\odot$ at ~240 Mpc (Abbott et al., 2020b). In neither case did the search for an optical or infrared counterpart return a positive result (Coughlin et al., 2019; Gomez et al., 2019; Ackley et al., 2020; Andreoni et al., 2020; Antier et al., 2020; Kasliwal, 2020), owing presumably to the large distance and sky error areas, although a short GRB may have been detected by the *INTEGRAL* SPI-ACS simultaneously with GW190425 (Pozanenko et al., 2019). Note that all coalescing stars may have been black holes, as the neutron star nature of the binary members lighter than 3 $M_\odot$ could not be confirmed.

The search for electromagnetic counterparts of gravitational radiation signals is currently thwarted primarily by the large uncertainty of their localization in the sky, which is usually no more accurate than several dozens of square degrees. Much smaller error boxes are expected to be available when the KAGRA (which had already joined LIGO-Virgo in the last months of the 2019–2020 observing run) and the INDIGO interferometers will operate at full regime as part of the network during the next observing run (Abbott et al., 2018). Observing modes, strategies, and simulations are being implemented to optimize the electromagnetic multiwavelength search and follow-up (Bartos et al., 2016; Patricelli et al., 2018; Cowperthwaite et al., 2019; Graham et al., 2019; Artale et al., 2020), and new dedicated space-based facilities are designed with critical capabilities of large sky area coverage and rapid turnaround (e.g., *ULTRASAT*, Sagiv et al., 2014; *THESEUS*, Amati et al., 2018, Stratta et al., 2018; *DORADO*, Cenko, 2019), to maximize the chance of detection of dim, fast-declining transients.

Finally, the possible detection of elusive MeV and >GeV neutrinos associated with the kilonova (Kyutoku and Kashiyama, 2018) and with the GRB (Bartos et al., 2019; Aartsen et al., 2020), respectively, will bring an extra carrier of information into play and thus complete the multimessenger picture associated with the binary neutron star merger phenomenon. Gravitational waves from binary neutron star inspirals and mergers; gamma-ray photons—downscattered to UV/optical/infrared light—from radioactive decay of unstable nuclides of heavy elements, freshly formed after the merger; multiwavelength photons from nonthermal mechanisms in the relativistic jet powered by the merger remnant; and thermal and high-energy neutrinos accompanying the remnant cooling and hadronic processes in the jet, respectively, all collectively underpin the role of the four physical interactions. This fundamental role of compact star merger phenomenology thus points to the formidable opportunity offered by a multimessenger approach: bringing the communities of astrophysicists and nuclear physicists closer will foster that cross-fertilization and interdisciplinary coordination that is not only beneficial but also essential for progress in this field.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

ACKNOWLEDGMENTS

The author is indebted to T. Belloni, S. Cristallo, Th. Janka, P. Mazzali, A. Possenti, M. Tanaka, and F. Thielemann for discussion. She acknowledges hospitality from Liverpool John Moores University, Weizmann Institute of Science, Rehovot, and the Hebrew University of Jerusalem, Israel; National Astronomical Observatory of Japan, Tokyo; Beihang University, Beijing; Yunnan National Astronomical Observatory, Kunming, China; and Max-Planck Institute for Astrophysics and Munich Institute for Astro- and Particle Physics, Garching, Germany, where part of this work was accomplished.

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Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.