Mergers of binary neutron star systems: a multi-messenger revolution

Elena Pian

\textsuperscript{1, *}

\textsuperscript{1} INAF, Astrophysics and Space Science Observatory

Correspondence*:
Via Piero Gobetti 101, 40129 Bologna, Italy
elena.pian@inaf.it

ABSTRACT

On 17 August 2017, less than two years after the direct detection of gravitational radiation from the merger of two $\sim 30 \, M_\odot$ black holes, a binary neutron star merger was identified as the source of a gravitational wave signal of $\sim 100 \, s$ duration that occurred at less than 50 Mpc from Earth. A short GRB 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 $\sim 10 \, \text{days}$, to the detection of radio and X-ray signals. This paper 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: neutron star, gravitational waves, gamma-ray burst, nucleosynthesis, r-process, kilonova

1 INTRODUCTION

Although the birth of "multi-messenger" astronomy dates back to the detection of the first solar neutrinos in the ’60s and was rejuvenated by the report of MeV neutrinos from SN1987A in the Large Magellanic Cloud, the detection of gravitational radiation from the binary neutron star merger on 17 August 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 that 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 $\sim 10^{42} \, \text{erg s}^{-1}$, 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 and 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 post-merger ejecta. Its evolution, as well as that of the GRB afterglow, was recorded with exquisite detail, thanks to its closeness (40 Mpc). Scope of this paper is to review the electromagnetic multi-wavelength observations of GW170817 with particular attention to the kilonova phenomenon.
The outline of the paper is as follows: Section 2 sets the context of binary systems of neutron 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 multi-wavelength features of its electromagnetic counterpart (short GRB and kilonova); Section 4 focuses 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 & Taylor, 1974), and the presence of its companion was inferred from the periodic changes in the observed pulsation period of 59 ms (Hulse & 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, signalled by the secular decrease of the 7.75 hours orbital period, that could be entirely attributed to energy loss via gravitational radiation (Taylor & Weisberg, 1982; Weisberg & Huang, 2016, and references therein).

With an orbital decay rate of \( \dot{P} = -2.4 \times 10^{-12} \text{ s}^{-1} \), the merging time of the PSR B1913+16 system is \( \sim 300 \text{ Myr} \). Following the detection of PSR B1913+16, another dozen 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 \( 110-3840 \text{ Gpc}^{-3} \text{ yr}^{-1} \) (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 25 April 2019 was produced by a binary neutron star coalescence the local rate of neutron star mergers would be updated to \( 250 - 2810 \text{ Gpc}^{-3} \text{ yr}^{-1} \) (Abbott et al., 2020a).

The merger of a binary neutron star system has three 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, as detailed in the next three sub-sections.

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 & 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 post-merger, 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 $\sim 200$ 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 100-1000 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 seconds (short or sub-second GRBs) and one around 20 seconds (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 & Bloom, 2006; Levan et al., 2016), sub-second 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 (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 versus 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 of these, \( \sim 100 \), \( \sim 40 \) and \( \sim 10 \) have a detected afterglow in X-rays, optical and radio wavelengths, respectively, and \( \sim 30 \) have measured redshifts (these range between \( z = 0.111 \) and \( z = 2.211 \), excluding the nearby GRB170817A, see Section 5.1.1 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 multi-wavelength 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 (Fong et al., 2015; Jin et al., 2018; Wang 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 not 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 \( ^{56}\text{Co} \)) of radioactive \( ^{56}\text{Ni} \) 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 \( \beta^- \) decay. In the s-process, neutron captures occur with timescales of hundreds to thousands of years, making \( \beta^- \) decay highly probable, while r-process neutron capture occurs on a timescale of \( \sim 0.01 \) seconds, leading to acquisition of many neutrons before \( \beta^- \) decay can set on. As a consequence, the s-process produces less unstable, longer-lived isotopes, close to the so-called valley of \( \beta^- \)-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; 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 neighbourhood these are seen as maxima (“peaks”) centered around atomic numbers \( Z = 39 \) (Sr-Y-Zr), \( 57 \) (Ba-La-Ce-Nd), \( 82 \) (Pb) for the s-process and, correspondingly somewhat lower atomic numbers \( Z = 35 \) (Se-Br-Kr), \( 53 \) (Te-I-Xe), \( 78 \) (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 \( ^{13}\text{C}(\alpha, n)^{16}\text{O} \) and \( ^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \) reactions (Busso et al., 1999). The r-process

\[ \text{http://www.mpe.mpg.de/~jcg/grbgen.html} \]
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.

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 proto-neutron stars (Woosley et al., 1994; Takahashi et al., 1994); 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 & Schramm, 1974, 1976; Symbalisty & 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 1000) and shorter duration (rise time of a few days) than supernova (Li & Paczyński, 1998).

The models for r-process elements production in core-collapse supernovae all have problems inherent 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 non-negligible binary evolution times (see Cowan et al., 2020 for an accurate review of all arguments in favour and against either channel). While the event of 17 August 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 (Ji et al., 2016; Ramirez-Ruiz et al., 2015; Côté et al., 2019; Safarzadeh et al., 2019; Simonetti et al., 2019). It cannot be excluded that both “weak” and “strong” r-process nucleosynthesis takes 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 & Ramirez-Ruiz, 2019) points to binary compact star mergers or very energetic (i.e. expansion velocities larger than 20000 km s$^{-1}$) core-collapse supernovae as progenitors, rather than regular core-collapse supernovae. Along these lines, Siegel et al. (2019) have proposed that the accretion disks of collapsars (the powerful core-collapse supernovae that accompany long GRBs, Woosley & Bloom, 2006) produce neutron-rich outflows that synthesize heavy r-process nuclei.

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 & Hotokezaka, 2019) where the neutron density rapidly drops to optimal values for r-process occurrence ($\sim 10^{21} - 32$ neutrons cm$^{-3}$, Freiburghaus et al., 1999) and for copious formation of neutron-rich stable and unstable isotopes of large atomic number elements (Fernández & 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 17 August 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 \((40^{+8}_{-14} \text{ Mpc})\), 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,c), 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 seconds before and 14 days after the merger returned no detections (Albert et al., 2017; Abe et al., 2018).

Based on the very detection of electromagnetic radiation, Bauswein et al. (2017) have argued that the merger remnant may not be a black hole or at least the post-merger collapse to a black hole may be delayed. Since the post-merger 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.

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 \textit{Fermi} satellite and the Anticoincidence Shield for the gamma-ray Spectrometer (SPI) of the \textit{International Gamma-Ray Astrophysics Laboratory (INTEGRAL)} satellite were triggered by a faint short GRB (duration of \(\sim 2\) seconds), 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 \(1.7\) seconds, 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 \(\sim 50\) 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 to 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 \(V \sim 17\), i.e. within \(\sim 12\) hours 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 1m telescope Swope at Las Campanas Observatory. The optical source lies at 10 arc-seconds angular separation, corresponding to a projected distance of \(\sim 2\) 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

This is a provisional file, not the final typeset article
the afterglows from misaligned GRB jets have longer rise-times than those of jets observed at small viewing angles (Van Eerten & MacFadyen, 2011). Therefore, X-ray monitoring with Swift/XRT, Chandra and Nustar continued, and \( \sim 10 \) days after merger led to the detection with Chandra of a faint source (\( L_X \sim 10^{40} \text{ erg s}^{-1} \)) (Evans et al., 2017; Margutti et al., 2017; Troja et al., 2017), whose intensity continued to rise up to \( \sim 100 \) days (D’Avanzo et al., 2018; Troja et al., 2020). Similarly, observations at cm and mm wavelengths at various arrays, including VLA and ALMA, failed to detect the source before \( \sim 16 \) 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 (\( \geq 20 \) degrees) 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 minutes after the merger, and did not detect any emission in the energy range 0.1-1 GeV to a limiting flux of \( 4.5 \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2} \) in the interval 1153-2027 seconds 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 \( \sim 5 \) days after merger returned no detection to a limit of a few \( 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) (Abdalla et al., 2017). A summary of the results of the multi-wavelength observing campaign within the first month of gravitational wave signal detection are 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 \( \leq 4 \) days at blue wavelengths from cooling of shock-heated material around the neutron star merger, Piro & Kollmeier, 2018), and later on by the afterglow, as described in the next two Sections.

### 3.1.1 The gamma-ray burst and its multi-wavelength afterglow

The short GRB170817A, with an energy output of \( \sim 10^{46} \text{ erg} \), was orders of magnitude dimmer than most short GRBs (Berger, 2014). Together with a viewing angle of \( \sim 30 \) 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 quasi-spherical 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 multi-wavelength afterglow (Lazzati et al., 2017a; Nakar & Piran, 2017; Bromberg et al., 2018; Xie et al., 2018), and is supported by detailed numerical simulations (Lazzati et al., 2018; Gottlieb et al., 2018).

Using milli-arcsecond 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) determine that, at 207 days, the source is still angularly smaller than 2 milli-arcseconds 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 (\( \theta_{\text{op}} \approx 3.4 \) degrees) and an energetic core (\( \sim 3 \times 10^{52} \text{ erg} \)) seen under a viewing angle of \( \sim 15 \) degrees (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 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 non-thermal 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, detected 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 blue-ward of the sampled wavelength range, suggesting that the initial temperature may have been larger than ~10000 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 3500-24000 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⊙ (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 ultra-relativistic 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). Early attempts at spectral modelling used best guesses and empirical approximate formulae, that are affected by a high level of uncertainty, and a very limited number of individual r-process elements may have been identified (e.g. strontium, Watson et al., 2019).

At ~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 post merger (Villar et al., 2018). The kilonova ejecta are also expected to interact with the circum-binary medium.
Binary neutron star mergers

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. This merger may be responsible for igniting weak nuclear activity (Levan et al., 2017). 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 low. Based on these data, the distance of NGC4993 was determined to be $(41.0 \pm 3.1)$ 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 $\sim 6\%$ $(40.7 \pm 1.4 \pm 1.9$ 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 down-scattered 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 to 71) series have full f-shells and therefore numerous atomic transitions that suppress the spectrum at shorter wavelengths ($\lesssim 8000 \AA$). Spectra of dynamical ejecta of kilonova may therefore be heavily intrinsically reddened, depending on the relative abundance of lanthanides (Barnes & Kasen, 2013; Kasen et al., 2013; Tanaka & 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, 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 & Metzger, 2013; Kiuchi et al., 2014; Metzger & Fernández, 2014; Perego et al., 2014; Kasen et al., 2015; Lippuner et al., 2017). This "post-merger" kilonova component, of preferentially polar direction, is thus relatively poor in lanthanides and gives rise to a less reddened spectrum (Tanaka et al., 2017; Kasen 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 de-convolved with the aid of a radiation transport model as it has been done for supernovae of all types (Mazzali et al., 2016; Ergon et al., 2018; Hillier & Dessart, 2019; Shingles et al., 2020; Ashall & Mazzali, 2020), a more fundamental hurdle in modelling 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 17 August 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 longterm 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 seconds, 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 ∼1000 at X-rays), the kilonova does not add significantly to the bright radio and X-ray afterglow component. Multi-epoch 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 sizeable 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 & Janka, 2001; Hotokezaka et al., 2013), how the jet forms and evolves, which kinematic regimes and geometry it takes up in time, and how can the GRB and afterglow observed phenomenologies help distinguish the intrinsic properties from viewing angle effects (Janka et al., 2006; Lamb & Kobayashi, 2018; Ioka & Nakamura, 2019), what is the detailed chemical content of kilonova ejecta 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 can kilonovae help constrain the binary neutron star rates and how does the parent population of short GRBs evolve (Guetta & Stella, 2009; Yang et al., 2017; Belczynski et al., 2018; Artale et al., 2019; Matsumoto & Piran, 2020), 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 in fact 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⊙, at ∼160 Mpc (Abbott et al., 2020a), and GW190814, caused by a 23 M⊙ black hole merging with a compact object of 2.6 M⊙ at 240 Mpc (Abbott et al., 2020b). In neither case did the search for an electromagnetic 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 et al., 2020), owing presumably to the large distance and sky error areas, but also possibly to the fact that all coalescing stars may have been black holes, as the neutron star nature of the binary members lighter than 3 M⊙ 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 multi-wavelength 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 et al. 2019), to maximize the chance of detection of dim, fast-declining transients.

Finally, the possible detection of MeV and >GeV neutrinos associated with the kilonova (Kyutoku & 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 multi-messenger picture associated with the binary neutron star merger phenomenon.

**CONFLICT OF INTEREST STATEMENT**

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.

**AUTHOR CONTRIBUTIONS**

The author is fully accountable for the content of this work.
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, and Yunnan National Astronomical Observatory, Kunming, China; Max-Planck Institute for Astrophysics and Munich Institute for Astro- and Particle Physics, Garching, Germany, where part of this work was accomplished.

DATA AVAILABILITY STATEMENT

The ESO VLT X-Shooter spectra reported in Figure I, first published in Pian et al. (2017) and Smartt et al. (2017), are available in the Weizmann Interactive Supernova Data Repository (https://wiserep.weizmann.ac.il; Yaron & Gal-Yam 2012).

REFERENCES

Aartsen, M. G., et al. (2020). IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo’s First Gravitational-wave Transient Catalog. Astrophys. J. 898, L10 doi:10.3847/2041-8213/ab9d24
Abbott, B.P., et al. (2016). Properties of the Binary Black Hole Merger GW150914. Phys. Rev. Lett. 116, 241102 doi:10.1103/PhysRevLett.116.241102
Abbott, B.P., et al. (2017a). GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. Phys. Rev. Lett. 119, 161101 doi:10.1103/PhysRevLett.119.161101
Abbott, B.P., et al. (2017b). Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. Astrophys. J. 848, L13 doi:10.3847/2041-8213/aa920c
Abbott, B.P., et al. (2017c). Multi-messenger Observations of a Binary Neutron Star Merger. Astrophys. J. 848, L12 doi:10.3847/2041-8213/aa91e9
Abbott, B.P., et al. (2017d). A gravitational-wave standard siren measurement of the Hubble constant. Nature 551, 85 doi:10.1038/nature24471
Abbott, B.P., et al. (2017e). Search for Post-merger Gravitational Waves from the Remnant of the Binary Neutron Star Merger GW170817. Astrophys. J. 851, L16 doi:10.3847/2041-8213/aa9a35
Abbott, B.P., et al. (2018). Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA. Living Reviews in Relativity 21, 3 doi:10.1007/s41114-018-0012-9
Abbott, B.P., et al. (2019). GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. Physical Review X 9, 031040 doi:10.1103/PhysRevX.9.031040
Abbott, B.P., et al. (2020a). GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_{\odot}$. Astrophys. J. 892, L3 doi:10.3847/2041-8213/ab75f5
Abbott, B.P., et al. (2020b). GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object. Astrophys. J. 896, L44 doi:10.3847/2041-8213/ab960f
Abdalla, H., et al. (2017). TeV Gamma-Ray Observations of the Binary Neutron Star Merger GW170817 with H.E.S.S.. Astrophys. J. 850, L22 doi:10.3847/2041-8213/aa97d2
Abe, K., et al. (2018). Search for Neutrinos in Super-Kamiokande Associated with the GW170817 Neutron-star Merger. *Astrophys. J.* 857, L4 doi:10.3847/2041-8213/aabaca

Ackley, K., et al. (2020). Observational constraints on the optical and near-infrared emission from the neutron star-black hole binary merger S190814bv. *Astr. & Astrophys.* in press (arXiv:2002.01950)

Ajello, M., et al. (2018). Fermi-LAT Observations of LIGO/Virgo Event GW170817. *Astrophys. J.* 861, 85 doi:10.3847/1538-4357/aac515

Albert, A., et al. (2017). Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory. *Astrophys. J.* 850, L35 doi:10.3847/2041-8213/aa9aed

Alexander, K.D., et al. (2017). The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejecta. *Astrophys. J.* 848, L21 doi:10.3847/2041-8213/aa905d

Amati, L., et al. (2018). The THESEUS space mission concept: science case, design and expected performances. *Adv. in Space Res.* 62, 191 doi:10.1016/j.asr.2018.03.010

Andreoni, I., et al. (2017). Follow Up of GW170817 and Its Electromagnetic Counterpart by Australian-Led Observing Programmes. *Pub. Astron. Soc. Au.* 34, 69 doi:10.1017/pasa.2017.65

Andreoni, I., et al. (2020). GROWTH on S190814bv: Deep Synoptic Limits on the Optical/Near-infrared Counterpart to a Neutron Star-Black Hole Merger. *Astrophys. J.* 890, 131 doi:10.3847/1538-4357/ab6a1b

Antier, S., et al. (2020). GRANDMA observations of advanced LIGO’s and advanced Virgo’s third observational campaign. *Mon. Not. R. Astr. Soc.* 497, 5518 doi:10.1093/mnras/staa1846

Antonelli, L. A., et al. (2009). GRB 090426: the farthest short gamma-ray burst? *Astr. & Astrophys.* 507, L45 doi:10.1051/0004-6361/200913062

Arcavi, I., et al. (2017). Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger. *Nature* 551, 64 doi:10.1038/nature24291

Artale, M. C., et al. (2019). Host galaxies of merging compact objects: mass, star formation rate, metallicity, and colours. *Mon. Not. R. Astr. Soc.* 487, 1675 doi:10.1093/mnras/stz1382

Artale, M. C., et al. (2020). An astrophysically motivated ranking criterion for low-latency electromagnetic follow-up of gravitational wave events. *Mon. Not. R. Astr. Soc.* 495, 1841 doi:10.1093/mnras/staa1252

Ashall, C., & Mazzali, P. (2020). Extracting high-level information from gamma-ray burst supernova spectra. *Mon. Not. R. Astr. Soc.* 492, 5956 doi:10.1093/mnras/staa212

Banerjee, P., et al. (2011). Long, Cold, Early r Process? Neutrino-Induced Nucleosynthesis in He Shells Revisited. *Phys. Rev. Lett.* 106, 201104 doi:10.1103/PhysRevLett.106.201104

Barnes, J., & Kasen, D. (2013). Effect of a High Opacity on the Light Curves of Radioactively Powered Transients from Compact Object Mergers. *Astrophys. J.* 775, 18 doi:10.1088/0004-637X/775/1/18

Bartos, I., et al. (2016). James Webb Space Telescope Can Detect Kilonovae in Gravitational Wave Follow-Up Search. *Astrophys. J.* 816, 61 doi:10.3847/0004-637X/816/2/61

Bartos, I., et al. (2019). Bayesian multimessenger search method for common sources of gravitational waves and high-energy neutrinos. *Phys. Rev. D* 100, 083017 doi:10.1103/PhysRevD.100.083017

Bauswein, A., et al. (2017). Neutron-star Radius Constraints from GW170817 and Future Detections. *Astrophys. J.* 850, L34 doi:10.3847/2041-8213/aa9994

Belczynski, K., et al. (2018). The origin of the first neutron star - neutron star merger. *Astr. & Astrophys.* 615, A91 doi:10.1051/0004-6361/201732428
Beniamini, P., et al. (2020). Ready, Set, Launch: Time Interval between a Binary Neutron Star Merger and Short Gamma-Ray Burst Jet Formation. *Astrophys. J.* 895, L33 doi:10.3847/2041-8213/ab9223

Berger, E., et al. (2013). An r-process Kilonova Associated with the Short-hard GRB 130603B. *Astrophys. J.* 774, L23 doi:10.1088/2041-8205/774/2/L23

Berger, E., (2014). Short-Duration Gamma-Ray Bursts. *Ann. Rev. Astron. Astrophys.* 52, 43 doi:10.1146/annurev-astro-081913-035926

Blanchard, P. K., et al. (2017). The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VII. Properties of the Host Galaxy and Constraints on the Merger Timescale. *Astrophys. J.* 848, L22 doi:10.3847/2041-8213/aa9055

Blanchet, L., et al. (2014). Gravitational Radiation from Post-Newtonian Sources and Inspiralling Compact Binaries. *Living Reviews in Relativity* 17, 2 doi:10.12942/lrr-2014-2

Bromberg, O., et al. (2013). Short versus Long and Collapsars versus Non-collapsars: A Quantitative Classification of Gamma-Ray Bursts. *Astrophys. J.* 764, 179 doi:10.1088/0004-637X/764/2/179

Bromberg, O., et al. (2018). The γ-rays that accompanied GW170817 and the observational signature of a magnetic jet breaking out of NS merger ejecta. *Mon. Not. R. Astr. Soc.* 475, 2971 doi:10.1093/mnras/stx3316

Burbidge, E., et al. (1957). Synthesis of the Elements in Stars. *Rev. Mod. Phys.* 29, 547 doi:10.1103/RevModPhys.29.547

Burns, E., et al. (2003). An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system. *Nature* 426, 531 doi:10.1038/nature02124

Burns, E., et al. (2016). Do the Fermi Gamma-Ray Burst Monitor and Swift Burst Alert Telescope see the Same Short Gamma-Ray Bursts? *Astrophys. J.* 818, 110 doi:10.3847/0004-637X/818/2/110

Busso, M., et al. (1999). Nucleosynthesis in Asymptotic Giant Branch Stars: Relevance for Galactic Enrichment and Solar System Formation *Ann. Rev. Astr. Astrophys.* 37, 239 doi:10.1146/annurev.astro.37.1.239

Cantiello, M., et al. (2018). A Precise Distance to the Host Galaxy of the Binary Neutron Star Merger GW170817 Using Surface Brightness Fluctuations. *Astrophys. J.* 854, L31 doi:10.3847/2041-8213/aaad64

Cenzo, S. B. (2019). The Gravitational-wave Ultraviolet Counterpart Imager (GUCl) Network. *American Astronomical Society Meeting Abstracts* 234, 212

Chornock, R., et al. (2017). The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. IV. Detection of Near-infrared Signatures of r-process Nucleosynthesis with Gemini-South. *Astrophys. J.* 848, L19 doi:10.3847/2041-8213/aa905c

Chruslinska, M., et al. (2018). Double neutron stars: merger rates revisited. *Mon. Not. R. Astr. Soc.* 474, 2937 doi:10.1093/mnras/stx2923

Côté, B., et al. (2018). The Origin of r-process Elements in the Milky Way. *Astrophys. J.* 855, 99 doi:10.3847/1538-4357/aad67

Côté, B., et al. (2019). Neutron Star Mergers Might Not Be the Only Source of r-process Elements in the Milky Way. *Astrophys. J.* 875, 106 doi:10.3847/1538-4357/ab10db

Coughlin, M. W., et al. (2019). GROWTH on S190425z: Searching Thousands of Square Degrees to Identify an Optical or Infrared Counterpart to a Binary Neutron Star Merger with the Zwicky Transient Facility and Palomar Gattini-IR. *Astrophys. J.* 885, L19 doi:10.3847/2041-8213/ab4ad8

Coulter, D. A., et al. (2017). Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source. *Science* 358, 1556 doi:10.1126/science.aap9811
Covino, S., et al. (2017). The unpolarized macronova associated with the gravitational wave event GW 170817. Nature Astr. 1, 791 doi:10.1038/s41550-017-0285-z

Cowan, J.J., et al. (2020). Origin of the Heaviest Elements: the Rapid Neutron-Capture Process. Rev. Mod. Phys., in press [arXiv:1901.01410]

Cowperthwaite, P. S., et al. (2017). The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. II. UV, Optical, and Near-infrared Light Curves and Comparison to Kilonova Models. Astrophys. J. 848, L17 doi:10.3847/2041-8213/aa8fc7

Cowperthwaite, P. S., et al. (2019). LSST Target-of-opportunity Observations of Gravitational-wave Events: Essential and Efficient. Astrophys. J., in press (arXiv:1901.01410)

D’Avanzo, P., et al. (2018). The evolution of the X-ray afterglow emission of GW 170817/GRB 170817A in XMM-Newton observations. Astr. & Astrophys. 613, L1 doi:10.1051/0004-6361/201832664

Davies, M. B., et al. (1994). Merging Neutron Stars. I. Initial Results for Coalescence of Noncorotating Systems. Astrophys. J. 431, 742 doi:10.1086/174525

Del Pozzo, W., et al. (2012). Inference of the cosmological parameters from gravitational waves: application to second generation interferometers. Phys. Rev. D 86, 043011 doi:10.1103/PhysRevD.86.043011

Díaz, M. C., et al. (2017). Observations of the First Electromagnetic Counterpart to a Gravitational-wave Source by the TOROS Collaboration. Astrophys. J. 848, L29 doi:10.3847/2041-8213/aa9060

Drout, M. R., et al. (2017). Light curves of the neutron star merger GW170817/SSS17a: Implications for r-process nucleosynthesis. Science 358, 1570 doi:10.1126/science.aaq0049

Eichler, D., et al. (1989). Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. Nature 340, 126 doi:10.1038/340126a0

Epstein, R.I., et al. (1988). Neutrino-induced r-process nucleosynthesis. Phys. Rev. Lett. 61, 2038 doi:10.1103/PhysRevLett.61.2038

Ergon, M., et al. (2018). Monte-Carlo methods for NLTE spectral synthesis of supernovae. Astr. & Astrophys. 620, A156 doi:10.1051/0004-6361/201833043

Evans, P.A., et al. (2017). Swift and NuSTAR observations of GW170817: Detection of a blue kilonova. Science 358, 1565 doi:10.1126/science.aap9580

Fernández, R., & Metzger, B.D. (2013). Delayed outflows from black hole accretion tori following neutron star binary coalescence. Mon. Not. R. Astr. Soc. 435, 502 doi:10.1093/mnras/stt1312

Fernández, R., & Metzger, B.D. (2016). Electromagnetic Signatures of Neutron Star Mergers in the Advanced LIGO Era. Annual Review of Nuclear and Particle Science 66, 23 doi:10.1146/annurev-nucl-102115-044819

Fong, W., et al. (2010). Hubble Space Telescope Observations of Short Gamma-Ray Burst Host Galaxies: Morphologies, Offsets, and Local Environments. Astrophys. J. 708, 9 doi:10.1088/0004-637X/708/1/9

Fong, W., et al. (2015). A Decade of Short-duration Gamma-Ray Burst Broadband Afterglows: Energetics, Circumburst Densities, and Jet Opening Angles. Astrophys. J. 815, 102 doi:10.1088/0004-637X/815/2/102

Fong, W., et al. (2019). The Optical Afterglow of GW170817: An Off-axis Structured Jet and Deep Constraints on a Globular Cluster Origin. Astrophys. J. 883, L1 doi:10.3847/2041-8213/ab3d9e

Fontes, C. J., et al. (2020). A line-binned treatment of opacities for the spectra and light curves from neutron star mergers. Mon. Not. R. Astr. Soc. 493, 4143 doi:10.1093/mnras/staa485

Freiburghaus, C., et al. (1999). R-Process in Neutron Star Mergers. Astrophys. J. 525, L121 doi:10.1086/312343
Fryer, C.L., et al. (2006). Supernova Fallback: A Possible Site for the r-Process. Astrophys. J. 646, L131 doi:10.1086/507071

Galama, T. J., et al. (1998). An unusual supernova in the error box of the γ-ray burst of 25 April 1998. Nature 395, 670 doi:10.1038/27150

Gehrels, N., et al. (2016). Galaxy Strategy for LIGO-Virgo Gravitational Wave Counterpart Searches. Astrophys. J. 820, 136 doi:10.3847/0004-637X/820/2/136

Ghirlanda, G., et al. (2019). Compact radio emission indicates a structured jet was produced by a binary neutron star merger. Science 363, 968 doi:10.1126/science.aau8815

Goldstein, A., et al. (2017). An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi-GBM Detection of GRB 170817A. Astrophys. J. 848, L14 doi:10.3847/2041-8213/aa8f41

Gomez, S., et al. (2019). A Galaxy-targeted Search for the Optical Counterpart of the Candidate NS-BH Merger S190814bv with Magellan. Astrophys. J. 884, L55 doi:10.3847/2041-8213/ab4ad5

Gompertz, B. P., et al. (2018). The Diversity of Kilonova Emission in Short Gamma-Ray Bursts. Astrophys. J. 860, 62 doi:10.3847/1538-4357/aac206

Gottlieb, O., et al. (2018). A cocoon shock breakout as the origin of the γ-ray emission in GW170817. Mon. Not. R. Astr. Soc. 479, 588 doi:10.1093/mnras/sty1462

Graham, M. J., et al. (2019). The Zwicky Transient Facility: Science Objectives. Publ. Astr. Soc. Pac. 131, 078001 doi:10.1088/1538-3873/ab006c

Guetta, D., & Stella, L. (2009). Short γ-ray bursts and gravitational waves from dynamically formed merging binaries. Astr. & Astrophys. 498, 329 doi:10.1051/0004-6361:200810493

Hajela, A., et al. (2019). Two Years of Nonthermal Emission from the Binary Neutron Star Merger GW170817: Rapid Fading of the Jet Afterglow and First Constraints on the Kilonova Fastest Ejecta. Astrophys. J. 886, L17 doi:10.3847/2041-8213/ab5226

Hallinan, G., et al. (2017). A radio counterpart to a neutron star merger. Science 358, 1579 doi:10.1126/science.aap9855

Hillebrandt, W., et al. (1976). r-process nucleosynthesis: a dynamical model. Astr. & Astrophys. 52, 63

Hillier, D. J., & Dessart, L. (2019). Photometric and spectroscopic diversity of Type II supernovae. Astr. & Astrophys. 631, A8 doi:10.1051/0004-6361/201935100

Hjorth, J., et al. (2017). The Distance to NGC 4993: The Host Galaxy of the Gravitational-wave Event GW170817. Astrophys. J. 848, L31 doi:10.3847/2041-8213/aa9110

Horowitz, C. J., et al. (2019). r-process nucleosynthesis: connecting rare-isotope beam facilities with the cosmos. Journal of Physics G: Nuclear and Particle Physics 46, 083001 doi:10.1088/1361-6471/ab0849

Hotokezaka, K., et al. (2013). Mass ejection from the merger of binary neutron stars. Phys. Rev. D 87, 024001 doi:10.1103/PhysRevD.87.024001

Hotokezaka, K., et al. (2019). A Hubble constant measurement from superluminal motion of the jet in GW170817. Nature Astr. 3, 940 doi:10.1038/s41550-019-0820-1

Hulse, R. A. & Taylor, J. H. (1974). A High-Sensitivity Pulsar Survey. Astrophys. J. 191, L59 doi:10.1086/181548

Hulse, R. A. & Taylor, J. H. (1975). Discovery of a pulsar in a binary system. Astrophys. J. 195, L51 doi:10.1086/181708

Im, M., et al. (2017). Distance and Properties of NGC 4993 as the Host Galaxy of the Gravitational-wave Source GW170817. Astrophys. J. 849, L16 doi:10.3847/2041-8213/aa9367

Ioka, K. & Nakamura, T. (1975). Spectral puzzle of the off-axis gamma-ray burst in GW170817. Mon. Not. R. Astr. Soc. 487, 4884 doi:10.1093/mnras/stz1650

This is a provisional file, not the final typeset article
Iwamoto, K., et al. (1998). A hypernova model for the supernova associated with the γ-ray burst of 25 April 1998. *Nature* 395, 672 doi:10.1038/27155

Janka, H.-Th., et al. (2006). Off-Axis Properties of Short Gamma-Ray Bursts. *Astrophys. J.* 645, 1305 doi:10.1086/504580

Ji, A. P., et al. (2016). R-process enrichment from a single event in an ancient dwarf galaxy. *Nature* 531, 610 doi:10.1038/nature17425

Jin, Z., et al. (2015). The Light Curve of the Macronova Associated with the Long-Short Burst GRB 060614. *Astrophys. J.* 811, L22 doi:10.1088/2041-8205/811/2/L22

Jin, Z., et al. (2016). The Macronova in GRB 050709 and the GRB-macronova connection. *Nature Comm.* 7, 12898 doi:10.1038/ncomms12898

Jin, Z., et al. (2018). Short GRBs: Opening Angles, Local Neutron Star Merger Rate, and Off-axis Events for GRB/GW Association. *Astrophys. J.* 857, 128 doi:10.3847/1538-4357/aab76d

Kajino, T., et al. (2019). Current status of r-process nucleosynthesis. *Progress in Particle and Nuclear Physics* 107, 109 doi:10.1016/j.ppnp.2019.02.008

Kasen, D., et al. (2013). Opacities and Spectra of the r-process Ejecta from Neutron Star Mergers. *Astrophys. J.* 774, 25 doi:10.1088/0004-637X/774/1/25

Kasen, D., et al. (2015). Kilonova light curves from the disc wind outflows of compact object mergers. *Mon. Not. R. Astr. Soc.* 450, 1777 doi:10.1093/mnras/stv721

Kasen, D., et al. (2017). Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event. *Nature* 551, 80 doi:10.1038/nature24453

Kasliwal, M.M., et al. (2017). Illuminating gravitational waves: A concordant picture of photons from a neutron star merger. *Science* 358, 1559 doi:10.1126/science.aap9455

Kasliwal, M.M., et al. (2020). Kilonova Luminosity Function Constraints based on Zwicky Transient Facility Searches for 13 Neutron Star Mergers. *Astrophys. J.*, in press (arXiv:2006.11306)

Kathirgamaraju, A., et al. (2019). Observable features of GW170817 kilonova afterglow. *Mon. Not. R. Astr. Soc.* 487, 3914 doi:10.1093/mnras/stz1564

Kim, S., et al. (2017). ALMA and GMRT Constraints on the Off-axis Gamma-Ray Burst 170817A from the Binary Neutron Star Merger GW170817. *Astrophys. J.* 850, L21 doi:10.3847/2041-8213/aa970b

Kiuchi, K., et al. (2014). High resolution numerical relativity simulations for the merger of binary magnetized neutron stars. *Phys. Rev. D* 90, 041502 doi:10.1103/PhysRevD.90.041502

Kouveliotou, C., et al. (1993). Identification of Two Classes of Gamma-Ray Bursts. *Astrophys. J.* 413, L101 doi:10.1086/186969

Kyutoku, K. & Kashiya, K. (2018). Detectability of thermal neutrinos from binary neutron-star mergers and implications for neutrino physics. *Phys. Rev. D* 97, 103001 doi:10.1103/PhysRevD.97.103001

Lamb, G. P. & Kobayashi, S. (2018). GRB 170817A as a jet counterpart to gravitational wave triggerGW 170817. *Mon. Not. R. Astr. Soc.* 478, 733 doi:10.1093/mnras/sty1108

Lamb, G. P., et al. (2019). Short GRB 160821B: A Reverse Shock, a Refreshed Shock, and a Well-sampled Kilonova. *Astrophys. J.* 883, 48 doi:10.3847/1538-4357/ab38bb

Lattimer, J.M. & Schramm, D.N. (1974). Black-Hole-Neutron-Star Collisions. *Astrophys. J.* 192, L145 doi:10.1086/181612

Lattimer, J.M. & Schramm, D.N. (1976). The tidal disruption of neutron stars by black holes in close binaries. *Astrophys. J.* 210, 549 doi:10.1086/154860

Lazzati, D., et al. (2017a). Off-axis emission of short gamma-ray bursts and the detectability of electromagnetic counterparts of gravitational-wave-detected binary mergers. *Mon. Not. R. Astr. Soc.* 471, 1652 doi:10.1093/mnras/stx1683
Lazzati, D., et al. (2017b). Off-axis Prompt X-Ray Transients from the Cocoon of Short Gamma-Ray Bursts. *Astrophys. J.* 848, L6 doi:10.3847/2041-8213/aa8f3d

Lazzati, D., et al. (2018). Late Time Afterglow Observations Reveal a Collimated Relativistic Jet in the Ejecta of the Binary Neutron Star Merger GW170817. *Phys. Rev. Lett.* 120, 241103 doi:10.1103/PhysRevLett.120.241103

Levan, A. J., et al. (2016). Gamma-Ray Burst Progenitors. *Space Science Rev.* 202, 33 doi:10.1007/s11214-016-0312-x

Levan, A. J., et al. (2017). The Environment of the Binary Neutron Star Merger GW170817. *Astrophys. J.* 848, L28 doi:10.3847/2041-8213/aa905f

Li, L.-X. & Paczyński, B. (1998). Transient Events from Neutron Star Mergers. *Astrophys. J.* 507, L59 doi:10.1086/311680

Lipunov, J., et al. (2017). Signatures of hypermassive neutron star lifetimes on r-process nucleosynthesis in the disc ejecta from neutron star mergers. *Mon. Not. R. Astr. Soc.* 472, 904 doi:10.1093/mnras/stx1987

Lipunov, V. M., et al. (2017). MASTER Optical Detection of the First LIGO/Virgo Neutron Star Binary Merger GW170817. *Astrophys. J.* 850, L1 doi:10.3847/2041-8213/aa92c0

Lyman, J. D., et al. (2018). The optical afterglow of the short gamma-ray burst associated with GW170817. *Nature Astr.* 2, 751 doi:10.1038/s41550-018-0511-3

Macias, P., & Ramirez-Ruiz, E. (2019). Constraining Collapsar r-process Models through Stellar Abundances. *Astrophys. J.* 877, L24 doi:10.3847/2041-8213/ab2049

Margutti, R., et al. (2017). The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. V. Rising X-Ray Emission from an Off-axis Jet. *Astrophys. J.* 848, L20 doi:10.3847/2041-8213/aa9057

Martinez, J. G., et al. (2017). Pulsar J1411+2551: A Low-mass Double Neutron Star System. *Astrophys. J.* 851, L29 doi:10.3847/2041-8213/aa9d87

Matsumoto, T., & Piran, T. (2020). On short GRBs similar to GRB 170817A detected by Fermi-GBM. *Mon. Not. R. Astr. Soc.* 492, 4283 doi:10.1093/mnras/staa050

Mazzali, P., et al. (2000). A Spectroscopic Analysis of the Energetic Type Ic Hypernova SN 1997ef. *Astrophys. J.* 545, 407 doi:10.1086/317808

Mazzali, P., et al. (2016). Spectrum formation in superluminous supernovae (Type I). *Mon. Not. R. Astr. Soc.* 458, 3455 doi:10.1093/mnras/stw512

McCully, C., et al. (2017). The Rapid Reddening and Featureless Optical Spectra of the Optical Counterpart of GW170817, AT 2017gfo, during the First Four Days. *Astrophys. J.* 848, L32 doi:10.3847/2041-8213/aa9111

Metzger, B.D., & Fernández, R. (2014). Red or blue? A potential kilonova imprint of the delay until black hole formation following a neutron star merger. *Mon. Not. R. Astr. Soc.* 441, 3444 doi:10.1093/mnras/stu802

Metzger, B.D. (2019). Kilonovae. *Living Reviews in Relativity* 23, 1 doi:10.1007/s41114-019-0024-0

Mooley, K., et al. (2018a). A mildly relativistic wide-angle outflow in the neutron-star merger event GW170817. *Nature* 554, 207 doi:10.1038/nature25452

Mooley, K., et al. (2018b). Superluminal motion of a relativistic jet in the neutron-star merger GW170817. *Nature* 561, 355 doi:10.1038/s41586-018-0486-3

Mooley, K., et al. (2018c). A Strong Jet Signature in the Late-time Light Curve of GW170817. *Astrophys. J.* 868, L11 doi:10.3847/2041-8213/aaeda7
Nakamura, T., et al. (2001). Light Curve and Spectral Models for the Hypernova SN 1998BW Associated with GRB 980425. *Astrophys. J.* 550, 991 doi:10.1086/319784

Nakano, H., et al. (2019). Comparison of various methods to extract ringdown frequency from gravitational wave data. *Phys. Rev. D* 99, 124032 doi:10.1103/PhysRevD.99.124032

Nakar, E. (2007). Short-hard gamma-ray bursts. *Phys. Rep.* 442, 166 doi:10.1016/j.physrep.2007.02.005

Nakar, E., & Piran, T. (2017). The Observable Signatures of GRB Cocoons. *Astrophys. J.* 834, 28 doi:10.3847/1538-4357/834/1/28

Nicholl, M., et al. (2017). The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. III. Optical and UV Spectra of a Blue Kilonova from Fast Polar Ejecta. *Astrophys. J.* 848, L18 doi:10.3847/2041-8213/aa9029

Ning, H., et al. (2007). r-Process Nucleosynthesis in Shocked Surface Layers of O-Ne-Mg Cores. *Astrophys. J.* 667, L159 doi:10.1086/522372

Nishimura, S., et al. (2006). r-Process Nucleosynthesis in Magnetohydrodynamic Jet Explosions of Core-Collapse Supernovae. *Astrophys. J.* 642, 410 doi:10.1086/500786

Nissanke, S., et al. (2010). Exploring Short Gamma-ray Bursts as Gravitational-wave Standard Sirens. *Astrophys. J.* 725, 496 doi:10.1088/0004-637X/725/1/496

Pan, Y. -C., et al. (2017). The Old Host-galaxy Environment of SSS17a, the First Electromagnetic Counterpart to a Gravitational-wave Source. *Astrophys. J.* 848, L30 doi:10.3847/2041-8213/aa9116

Pandey, S. B., et al. (2019). A multiwavelength analysis of a collection of short-duration GRBs observed between 2012 and 2015. *Mon. Not. R. Astr. Soc.* 485, 5294 doi:10.1093/mnras/stz530

Patri古城, B., et al. (2018). Searching for gamma-ray counterparts to gravitational waves from merging binary neutron stars with the Cherenkov Telescope Array. *J. Cosm. & Astroparticle Phys.* 5, 056 doi:10.1088/1475-7516/2018/05/056

Perego, A., et al. (2014). Neutrino-driven winds from neutron star merger remnants. *Mon. Not. R. Astr. Soc.* 443, 3134 doi:10.1093/mnras/stu1352

Pfahl, E., et al. (2005). Relativistic Binary Pulsars with Black Hole Companions. *Astrophys. J.* 628, 343 doi:10.1086/430515

Pian, E., et al. (2017). Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger. *Nature* 551, 67 doi:10.1038/nature24298

Piro, A. L. and Kollmeier, J. A. (2018). Evidence for Cocoon Emission from the Early Light Curve of SSS17a. *Astrophys. J.* 855, 103 doi:10.3847/1538-4357/aaaab3

Pozanenko, A.S., et al. (2018). GRB 170817A Associated with GW170817: Multi-frequency Observations and Modeling of Prompt Gamma-Ray Emission. *Astrophys. J.* 852, L30 doi:10.3847/2041-8213/aaa2f6

Ramirez-Ruiz, E., et al. (2015). Compact Stellar Binary Assembly in the First Nuclear Star Clusters and r-process Synthesis in the Early Universe. *Astrophys. J.* 802, L22 doi:10.1088/2041-8205/802/2/L22

Rauscher, T., et al. (1994). Production of Heavy Elements in Inhomogeneous Cosmologies. *Astrophys. J.* 429, 499 doi:10.1086/174339

Renzo, M., et al. (2019). Massive runaway and walkaway stars. A study of the kinematical imprints of the physical processes governing the evolution and explosion of their binary progenitors. *Astr. & Astrophys.* 624, A66 doi:10.1051/0004-6361/201833297

Rossi, A., et al. (2020). A comparison between short GRB afterglows and kilonova AT2017gfo: shedding light on kilonovae properties. *Mon. Not. R. Astr. Soc.* 493, 3379 doi:10.1093/mnras/staa4794

Rosswog, S., et al. (1999). Mass ejection in neutron star mergers. *Astr. & Astrophys.* 341, 499
Rosswog, S., et al. (2018). The first direct double neutron star merger detection: Implications for cosmic nucleosynthesis. *Astr. & Astrophys.* 615, A132 doi:10.1051/0004-6361/201732117

Ruffert, M. and Janka, H.-Th. (2001). Coalescing neutron stars - A step towards physical models. III. Improved numerics and different neutron star masses and spins. *Astr. & Astrophys.* 380, 544 doi:10.1051/0004-6361:20011453

Safarzadeh, M., et al. (2019). On Neutron Star Mergers as the Source of r-process-enhanced Metal-poor Stars in the Milky Way. *Astrophys. J.* 876, 28 doi:10.1088/2041-8205/802/2/L22

Sagiv, I., et al. (2014). Science with a Wide-field UV Transient Explorer. *Astr. J.* 147, 79 doi:10.1088/0004-6256/147/4/79

Salafia, O. S., et al. (2018). Interpreting GRB170817A as a giant flare from a jet-less double neutron star merger. *Astr. & Astrophys.* 619, A18 doi:10.1051/0004-6361/201732259

Sana, H., et al. (2012). Binary Interaction Dominates the Evolution of Massive Stars. *Science* 337, 444 doi:10.1126/science.1223344

Savchenko, V., et al. (2017). INTEGRAL Detection of the First Prompt Gamma-Ray Signal Coincident with the Gravitational-wave Event GW170817. *Astrophys. J.* 848, L15 doi:10.3847/2041-8213/aa8f94

Schutz, B. F. (1986). Determining the Hubble constant from gravitational wave observations. *Nature* 323, 310 doi:10.1038/323310a0

Shapiro, S. L., & Teukolsky, S. A. (1983). Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects. doi:10.1002/9783527617661

Shappee, B. J., et al. (2017). Early spectra of the gravitational wave source GW170817: Evolution of a neutron star merger. *Science* 358, 1574 doi:10.1126/science.aaq0186

Shibata, M., & Hotokezaka, K. (2019). Neutron Star Collisions and the r-Process. *Annual Review of Nuclear and Particle Science* 69, 41 doi:10.1146/annurev-nucl-101918-023625

Shingles, L. J., et al. (2020). Monte Carlo radiative transfer for the nebular phase of Type Ia supernovae. *Mon. Not. R. Astr. Soc.* 492, 2029 doi:10.1093/mnras/stz3412

Siegel, D. M., et al. (2019). Collapsars as a major source of r-process elements. *Nature* 569, 241 doi:10.1038/s41586-019-1136-0

Simonetti, P., et al. (2019). A new delay time distribution for merging neutron stars tested against Galactic and cosmic data. *Mon. Not. R. Astr. Soc.* 486, 2896 doi:10.1093/mnras/stt991

Smartt, S.J., et al. (2017). A kilonova as the electromagnetic counterpart to a gravitational-wave source. *Nature* 551, 75 doi:10.1038/nature24303

Sneden, C., et al. (2008). Neutron-capture elements in the early galaxy. *Ann. Rev. Astr. Astrophys.* 46, 241 doi:10.1146/annurev.astro.46.060407.145207

Soares-Santos, M., et al. (2017). The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera. *Astrophys. J.* 848, L16 doi:10.3847/2041-8213/aa9059

Stratta, G., et al. (2018). THESEUS: A key space mission concept for Multi-Messenger Astrophysics. *Adv. in Space Res.* 62, 662 doi:10.1016/j.asr.2018.04.013

Symbalisty, E., & Schramm, D. N. (1982). Neutron Star Collisions and the r-Process. *Astrophys. Lett.* 22, 143

Takahashi, K., et al. (1994). Nucleosynthesis in neutrino-driven winds from protoneutron stars II. The r-process. *Astr. & Astrophys.* 286, 857

Tanaka, M., & Hotokezaka, K. (2013). Radiative Transfer Simulations of Neutron Star Merger Ejecta. *Astrophys. J.* 775, 113 doi:10.1088/0004-637X/775/2/113
Tanaka, M. (2016). Kilonova/Macronova Emission from Compact Binary Mergers. *Advances in Astronomy* 2016, 634197 doi:10.1155/2016/6341974

Tanaka, M., et al. (2017). Kilonova from post-merger ejecta as an optical and near-Infrared counterpart of GW170817. *Publ. Astr. Soc. Japan* 69, 102 doi:10.1093/pasj/pxs121

Tanaka, M., et al. (2018). Properties of Kilonovae from Dynamical and Post-merger Ejecta of Neutron Star Mergers. *Astrophys. J.* 852, 109 doi:10.3847/1538-4357/aaa0cb

Tanaka, M., et al. (2020). Systematic opacity calculations for kilonovae. *Mon. Not. R. Astr. Soc.* 496, 1369 doi:10.1093/mnras/staa1576

Tanvir, N. R., et al. (2013). A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B. *Nature* 500, 547 doi:10.1038/nature12505

Tanvir, N. R., et al. (2017). The Emergence of a Lanthanide-rich Kilonova Following the Merger of Two Neutron Stars. *Astrophys. J.* 848, L27 doi:10.3847/2041-8213/aa90b6

Tauris, M. T., et al. (2017). Formation of double neutron star systems. *Astrophys. J.* 846, 170 doi:10.3847/1538-4357/aa7e89

Taylor, J. H., & Weisberg, J. M. (1982). A new test of general relativity - Gravitational radiation and the binary pulsar PSR 1913+16. *Astrophys. J.* 253, 908 doi:10.1086/159690

Thielemann, F.-K., et al. (2011). What are the astrophysical sites for the r-process and the production of heavy elements?. *Progress in Particle and Nuclear Physics* 66, 346 doi:10.1016/j.ppnp.2011.01.032

Tominaga, N., et al. (2018). Subaru Hyper Suprime-Cam Survey for an optical counterpart of GW170817. *Publ. Astr. Soc. Japan* 70, 28 doi:10.1093/pasj/psy007

Troja, E., et al. (2017). The X-ray counterpart to the gravitational-wave event GW170817. *Nature* 551, 71 doi:10.1038/nature24290

Troja, E., et al. (2020). A thousand days after the merger: continued X-ray emission from GW170817. *Mon. Not. R. Astr. Soc.*, in press (arXiv:2006.01150)

Utsumi, Y., et al. (2017). J-GEM observations of an electromagnetic counterpart to the neutron star merger GW170817. *Publ. Astr. Soc. Japan* 69, 101 doi:10.1093/pasj/psx118

Valenti, S., et al. (2017). The Discovery of the Electromagnetic Counterpart of GW170817: Kilonova AT 2017gfo/DLT17ck. *Astrophys. J.* 848, L24 doi:10.3847/2041-8213/aa8edf

van Eerten, H. J. & MacFadyen, A. I. (2011). Synthetic Off-axiss Light Curves for Low-energy Gamma-Ray Bursts. *Astrophys. J.* 733, L37 doi:10.1088/2041-8205/733/2/L37

Villar, V. A., et al. (2017). The Combined Ultraviolet, Optical, and Near-infrared Light Curves of the Kilonova Associated with the Binary Neutron Star Merger GW170817: Unified Data Set, Analytic Models, and Physical Implications. *Astrophys. J.* 851, L21 doi:10.3847/2041-8213/aa9c84

Villar, V. A., et al. (2018). Spitzer Space Telescope Infrared Observations of the Binary Neutron Star Merger GW170817. *Astrophys. J.* 862, L11 doi:10.3847/2041-8213/aad281

Wallner, A., et al. (2015). Abundance of live 244Pu in deep-sea reservoirs on Earth points to rarity of actinide nucleosynthesis. *Nature Comm.* 6, 5956 doi:10.1038/ncomms6956

Wang, X.-G., et al. (2018). The r-Process in the Neutrino Winds of Core-Collapse Supernovae and U-Th Cosmochronology. *Astrophys. J.* 577, 853 doi:10.1086/342230

Wang, X.-G., et al. (2018). Gamma-Ray Burst Jet Breaks Revisited. *Astrophys. J.* 859, 160 doi:10.3847/1538-4357/aaac13

Watson, D., et al. (2019). Identification of strontium in the merger of two neutron stars. *Nature* 574, 497 doi:10.1038/s41586-019-1676-3

Waxman, E., et al. (2018). Constraints on the ejecta of the GW170817 neutron star merger from its electromagnetic emission. *Mon. Not. R. Astr. Soc.* 481, 3423 doi:10.1093/mnras/sty2441
Weisberg, J. M., & Huang, Y. (2016). Relativistic Measurements from Timing the Binary Pulsar PSR B1913+16. *Astrophys. J.* 829, 55 doi:10.3847/0004-637X/829/1/55

Wheeler, J. C., et al. (1998). The r-Process in Collapsing O/Ne/Mg Cores. *Astrophys. J.* 493, L101 doi:10.1086/311133

Winteler, C., et al. (2012). Magnetorotationally Driven Supernovae as the Origin of Early Galaxy r-process Elements?. *Astrophys. J.* 750, L22 doi:10.1088/2041-8205/750/1/L22

Wollaeger, R. T., et al. (2018). Impact of ejecta morphology and composition on the electromagnetic signatures of neutron star mergers. *Mon. Not. R. Astr. Soc.* 478, 3298 doi:10.1093/mnras/sty1018

Wolszczan, A. (1991). A nearby 37.9-ms radio pulsar in a relativistic binary system. *Nature* 350, 688 doi:10.1038/350688a0

Woosley, S. E., et al.(1994). The r-Process and Neutrino-heated Supernova Ejecta. *Astrophys. J.* 433, 229 doi:10.1086/174638

Woosley, S. E., & Bloom, J. S.(2006). The Supernova Gamma-Ray Burst Connection. *Ann. Rev. Astr. Astrophys.* 44, 507 doi:10.1146/annurev.astro.43.072103.150558

Xie, X., et al.(2018). Numerical Simulations of the Jet Dynamics and Synchrotron Radiation of Binary Neutron Star Merger Event GW170817/GRB 170817A. *Astrophys. J.* 863, 58 doi:10.3847/1538-4357/aacf9c

Yang, S., et al. (2017). An Empirical Limit on the Kilonova Rate from the DLT40 One Day Cadence Supernova Survey. *Astrophys. J.* 851, L48 doi:10.3847/2041-8213/aaa07d

Yaron, O., & Gal-Yam, A. (2012). WISEREP—An Interactive Supernova Data Repository. *Publ. Astr. Soc. Pacific* 124, 668 doi:10.1086/666656

Ye, C. S., et al. (2020). On the Rate of Neutron Star Binary Mergers from Globular Clusters. *Astrophys. J.* 888, L10 doi:10.3847/2041-8213/ab5dc5

**FIGURE CAPTION**
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, de-redshifted, and offset in flux by multiples of $5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ additive constant with respect to the 10.5d spectrum. Wavelength ranges of poor atmospheric transmission were blanked out. Some spectra have been re-calibrated with respect to the originally published version, courtesy of J. Gillanders, J. Selsing and S. Smartt.
This figure "figure1_xsspectra.jpg" is available in "jpg" format from:

http://arxiv.org/ps/2009.12255v1