Publication Year	2020
Acceptance in OA@INAF	2023-10-04T14:58:02Z
Title	Binary Neutron Star Mergers After GW170817
Authors	CIOLFI, RICCARDO
DOI	10.3389/fspas.2020.00027
Handle	http://hdl.handle.net/20.500.12386/34432
Journal	FRONTIERS IN ASTRONOMY AND SPACE SCIENCES
Number	7

frontiers in Astronomy and Space Sciences

MINI REVIEW
published: 30 June 2020
doi: 10.3389/fspas.2020.00027

Binary Neutron Star Mergers After GW170817

Riccardo Ciolfi [1,2]*

[1] INAF–Osservatorio Astronomico di Padova, Padova, Italy, [2] INFN–Sezione di Padova, Padova, Italy

The first combined detection of gravitational waves and electromagnetic signals from a binary neutron star (BNS) merger in August 2017 (an event named GW170817) represents a major landmark in the ongoing investigation of these extraordinary systems. In this short review, we discuss BNS mergers as events of utmost importance for astrophysics and fundamental physics and survey the main discoveries enabled by this first multimessenger observation, including compelling evidence that such mergers produce a copious amount of heavy r-process elements and can power short gamma-ray bursts. We further discuss some remaining key open questions regarding this event and BNS mergers in general, focusing on the current status and limitations of theoretical models and numerical simulations.

Keywords: neutron stars, compact binary mergers, gravitational waves, multimessenger astrophysics, gamma-ray burst, kilonova

OPEN ACCESS

Edited by:
Bruno Giacomazzo,
University of Milano-Bicocca, Italy

Reviewed by:
Brian Metzger,
Columbia University, United States
Wen-Biao Han,
Chinese Academy of Sciences, China

***Correspondence:**
Riccardo Ciolfi
riccardo.ciolfi@inaf.it

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

Received: 19 March 2020
Accepted: 06 May 2020
Published: 30 June 2020

Citation:
Ciolfi R (2020) Binary Neutron Star
Mergers After GW170817.
Front. Astron. Space Sci. 7:27.
doi: 10.3389/fspas.2020.00027

INTRODUCTION

Binary neutron star (BNS) mergers are among the most intriguing events known in the universe, with impressive scientific potential spanning many different research fields in physics and astrophysics. Investigating these mergers offers a unique opportunity to understand hadronic interactions at supranuclear densities and the equations of state (EOS) of matter in such extreme conditions while gaining crucial insights into the strong gravity regime, high-energy astrophysical phenomena of primary importance, such as gamma-ray bursts (GRBs), the origin of heavy elements in the local universe, formation channels of compact object binaries, and cosmology (see e.g., Faber and Rasio, 2012; Baiotti and Rezzolla, 2017 and references therein).

The merger of two neutron stars (NSs) is accompanied by a strong emission of gravitational waves (GWs) and a rich variety of electromagnetic (EM) signals covering the entire spectrum, from gamma-rays to radio. Such a unique combination of signals makes these systems ideal multimessenger sources and allows us to observe them up to cosmological distances. Moreover, among their EM "counterparts," BNS mergers have long been thought to be responsible for short gamma-ray bursts (SGRBs) (Paczynski, 1986; Eichler et al., 1989; Narayan et al., 1992; Barthelmy et al., 2005; Fox et al., 2005; Gehrels et al., 2005; Berger, 2014) as well as radioactively powered "kilonova" transients associated with r-process nucleosynthesis of heavy elements (Li and Paczyński, 1998; Rosswog, 2005; Metzger et al., 2010)[1].

---

[1] Merging mixed binaries, each composed of an NS and a black hole (BH), share most of the above features, also being promising GW sources, potential SGRB central engines, and potential sources of radioactively powered kilonovae. However, the properties of the emitted signals could be very different. Here we focus on BNS mergers only and refer the reader to other reviews (e.g., Shibata and Taniguchi, 2011) for the case of NS-BH binary mergers.

A major step forward in the study of BNS mergers was made possible by the first GW detection for this type of event by the LIGO and Virgo Collaboration in August 2017 (an event known as GW170817) (Abbott et al., 2017d). This merger was also observed in the EM spectrum, via a collection of gamma-ray, X-ray, ultraviolet (UV), optical, infrared (IR), and radio signals, thus also providing the first multimessenger observation of a GW source (Abbott et al., 2017e). This breakthrough led to a number of key discoveries, including a striking confirmation that BNS mergers can launch SGRB jets (Abbott et al., 2017c; Alexander et al., 2017, 2018; Goldstein et al., 2017; Hallinan et al., 2017; Margutti et al., 2017; Savchenko et al., 2017; Troja et al., 2017; Lazzati et al., 2018; Lyman et al., 2018; Mooley et al., 2018a,b; Ghirlanda et al., 2019) and are ideal sites for r-process nucleosynthesis (e.g., Arcavi et al., 2017; Coulter et al., 2017; Kasen et al., 2017; Pian et al., 2017; Smartt et al., 2017; see also Metzger, 2019 and references therein), the first GW-based constraints on the NS EOS (Abbott et al., 2019) and the Hubble constant (Abbott et al., 2017b), and more. The most important lessons learned from this event are discussed in section .

Besides the remarkable results mentioned above, the GW170817 event also raised a number of questions, some relating to details of the merging process that remained only poorly constrained. For instance, the remnant object resulting from the merger appears most likely to be a metastable massive NS that eventually collapsed into a BH, but the lack of clear indications of its survival time until collapse leaves doubts regarding the nature of the SGRB central engine, which could have been either the massive NS or the accreting BH (see e.g., Ciolfi, 2018 for a recent review). Theoretical modeling of the merger process via general relativistic magnetohydrodynamics (GRMHD) simulations (see **Figure 1**) offers the best chance to tackle the open questions and to establish a reliable connection between the merger and post-merger dynamics and the observable GW and EM emission (e.g., Ciolfi, 2020b and references therein). In section , we briefly report on the status of the research in this direction, with reference to specific challenges posed by the GW170817 event. Finally, concluding remarks are given in section .

THE BNS MERGER OF AUGUST 2017

The characteristic "chirp" signal of GW170817, with both frequency and amplitude increasing over time up to a maximum, leaves no doubt that the source was a merging compact binary with component masses fully consistent with two NSs (Abbott et al., 2017d). In addition, the BNS nature of the source is arguably reinforced by the EM counterparts observed along with GWs (Abbott et al., 2017e). Under the BNS assumption, this single detection significantly improved our estimate for the corresponding local coalescence rate (the value reported in Abbott et al., 2017d being $R = 1540^{+3200}_{-1220}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$)[2].

For this event, most of the information inferred from GWs came from the inspiral phase up to merger, while the lower detector sensitivity at frequencies above 1 kHz did not allow for a confident detection of the post-merger signal (Abbott et al., 2017d). Despite such limitations, it was possible to start placing the first limits on the NS tidal deformability and thus constrain the range of NS EOS compatible with the event (see e.g., Abbott et al., 2019; Kastaun and Ohme, 2019) by measuring finite-size effects (i.e., deviations from the point-mass waveform) in the last orbits of the inspiral. Moreover, by combining the luminosity distance derived from GWs with the EM redshift measurement that the identification of the host galaxy (NGC 4993) allowed, it was possible to obtain the first constraints on the Hubble constant based on a GW standard siren determination (Abbott et al., 2017b).

The observation of a gamma-ray signal emerging about 1.74 s after the estimated time of merger enabled us to confirm that GWs propagate at the speed of light with a precision better than 10^{-14} (Abbott et al., 2017c), which excluded a whole range of gravitational theories beyond general relativity. At the same time, this high-energy signal (called GRB 170817A) was found to be potentially consistent with an SGRB, albeit orders of magnitude less energetic than any other known SGRB (Abbott et al., 2017c). Combining the prompt gamma-ray emission with the multiwavelength afterglows (in X-ray, optical, and radio) monitored for several months, it was possible to eventually converge to the following picture (Abbott et al., 2017c; Alexander et al., 2017, 2018; Goldstein et al., 2017; Hallinan et al., 2017; Margutti et al., 2017; Savchenko et al., 2017; Troja et al., 2017; Lazzati et al., 2018; Lyman et al., 2018; Mooley et al., 2018a,b; Ghirlanda et al., 2019): (i) the merger remnant launched a highly relativistic jet (Lorentz factor > 10), in agreement with the consolidated GRB paradigm (e.g., Piran, 2004; Kumar and Zhang, 2015); (ii) the burst was observed off-axis by 15–30°, and the low-energy gamma-ray signal detected was not produced by the jet core but rather by a mildly relativistic outflow moving along the line of sight; (iii) the on-axis observer would have seen a burst energetically consistent with the other known SGRBs. This provided the long-awaited compelling evidence that *BNS mergers can generate SGRBs*. Furthermore, the off-axis view of a nearby ($\sim$ 40 Mpc distance) SGRB jet gave us an unprecedented opportunity to study its full angular structure.

The other major result related to GW170817 is the first clear photometric and spectroscopic identification of a kilonova, i.e., a UV/optical/IR transient powered by the radioactive decay of heavy r-process elements synthesized within the matter ejected by the merger process (e.g., Arcavi et al., 2017; Coulter et al., 2017; Kasen et al., 2017; Pian et al., 2017; Smartt et al., 2017; see also Metzger, 2019 and references therein). This confirmed that *BNS mergers produce a significant amount of elements heavier than iron, up to very large atomic mass numbers* ($A > 140$).

OPEN QUESTIONS AND ONGOING RESEARCH

The discoveries connected with GW170817 certainly represent a breakthrough in the field, but a lot remains to be understood concerning both this event and BNS mergers in general. Part of

---

[2] Under the assumption that GW190425 was also a BNS merger, the updated rate would be $R = 250\text{–}2810\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (Abbott et al., 2020).

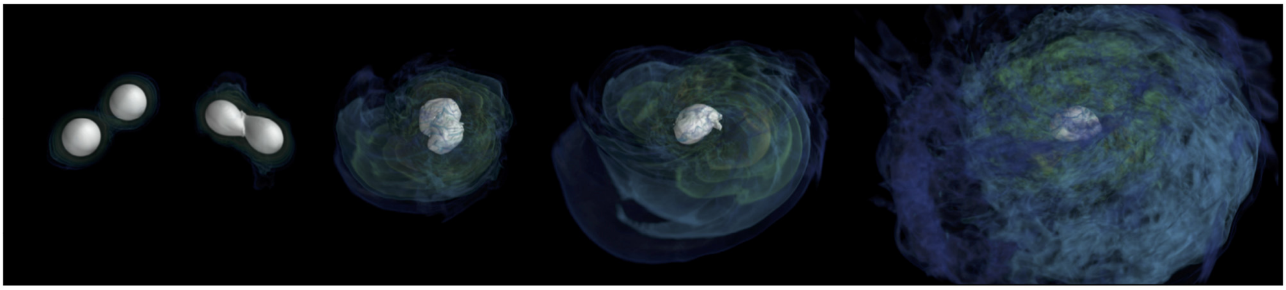

FIGURE 1 | Example of BNS merger simulation in GRMHD (from the models presented in Ciolfi et al., 2017). The temporal sequence shows the bulk of the NS(s) in white together with color-coded isodensity surfaces.

our ignorance can be ascribed to current observational limits. For instance, much better constraints on the NS EOS will become available with the considerably higher sensitivity of third-generation GW detectors (Punturo et al., 2010; Abbott et al., 2017a), allowing also for confident detection of the post-merger GW signal, while the merger rate, the formation scenarios of BNS systems, and the GW-based Hubble constant determination will improve greatly with the increasing number of detections. On the other hand, there are many aspects for which the information encoded in the observed signals (in particular in the EM counterparts) cannot be fully exploited because of the present limitations of theoretical models. This situation urgently calls for further development on the theory side, particularly in the context of BNS merger simulation in general relativity, which represents the leading approach to elucidating the physical mechanisms at work when two NSs merge.

In the following, we discuss recent results of BNS merger simulations and the associated limitations, focusing on interpretation of the August 2017 event. In particular, we consider the two most important EM counterparts of this event: (i) the SGRB and its multiwavelength afterglows, and (ii) the kilonova transient.

SGRB Central Engines and GRB 170817A

Understanding the launching mechanism of an SGRB jet from a BNS merger and the nature of the remnant object acting as central engine is among the main motivations for the development of numerical relativity simulations of such mergers (e.g., Rezzolla et al., 2011; Kiuchi et al., 2014; Kawamura et al., 2016; Ruiz et al., 2016; Ciolfi et al., 2017, 2019). The great progress made in this type of simulation, especially over the past decade, has allowed us to draw important conclusions, even though the final solution of the SGRB puzzle is still ahead of us.

According to the most discussed scenario, an SGRB jet would be launched by a spinning BH surrounded by a massive ($\sim 0.1\,M_{\odot}$) accretion disk, which is a likely outcome of a BNS merger. Recent simulations (Just et al., 2016; Perego et al., 2017b) have shown that a jet powered by neutrino-antineutrino annihilation would not be powerful enough to explain the phenomenology of SGRBs, reinforcing the idea that SGRB jets should instead be magnetically driven. Various GRMHD simulations (e.g., Rezzolla et al., 2011; Kiuchi et al., 2014; Kawamura et al., 2016; Ruiz et al., 2016) have explored the latter possibility, confirming the formation of a low-density funnel along the BH spin axis and finding indications of an emerging helical magnetic field structure that is favorable for accelerating an outflow. In addition, simulations reported in Ruiz et al. (2016) were the first to show the actual production of a magnetically dominated mildly relativistic outflow, and the authors argued that such an outflow could in principle reach terminal Lorentz factors compatible with an SGRB jet. While the results obtained so far do not provide the ultimate answer, current simulations suggest that the accreting BH scenario is a promising one (see e.g., Ciolfi, 2018, 2020b for a more detailed discussion).

The alternative scenario in which the central engine is a massive NS remnant has also been investigated via GRMHD BNS merger simulations, although a systematic study commenced only recently (Ciolfi et al., 2017, 2019; Ciolfi, 2020a). In this case, the higher level of baryon pollution along the spin axis could hamper the formation of an incipient jet. The longest (to date) simulations of this kind, recently presented in Ciolfi (2020a), showed for the first time that the NS differential rotation can still build up a helical magnetic field structure capable of accelerating a collimated outflow (see **Figure 2**), although such an outcome is not ubiquitous[3]. In addition, for the case under consideration, the properties of the collimated outflow (and in particular the very low terminal Lorentz factor) were found to be largely incompatible with an SGRB jet (Ciolfi, 2020a). This result reveals serious difficulties in powering an SGRB that might apply to massive NS remnants in general, thus pointing in favor of the alternative BH central engine. In order to confirm the above conclusion, however, a greater variety of physical conditions needs to be explored (e.g., by including neutrino radiation).

For the GRB 170817A event, neither the observations nor the current theoretical models can confidently exclude either one of the two scenarios. Nevertheless, BNS merger simulations have already provided valuable hints in favor of the accreting BH scenario (Ruiz et al., 2016; Ciolfi, 2020a), and the continuous

---

[3] Note that a collimated outflow was also reported in studies where an *ad-hoc* dipolar field was superimposed by hand on a differentially rotating NS remnant (e.g., Shibata et al., 2011; Siegel et al., 2014; Mösta et al., 2020).

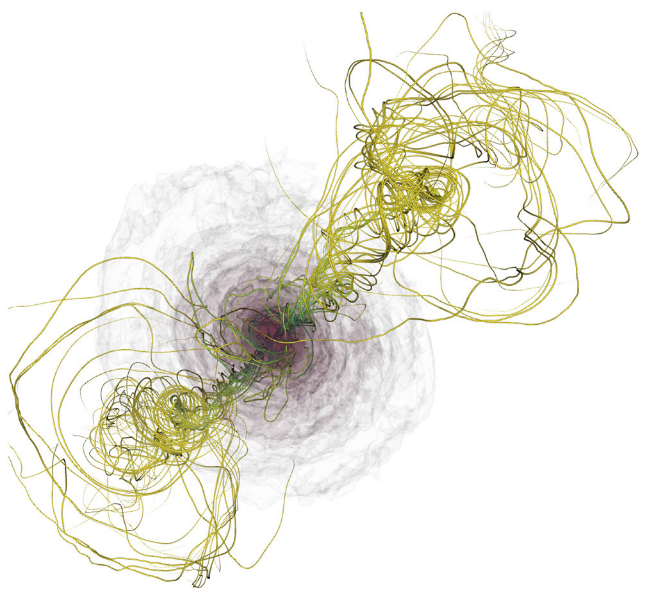

FIGURE 2 | Collimated helical magnetic field structure emerging along the spin axis of a long-lived BNS merger remnant (from a simulation presented in Ciolfi, 2020a). Several semi-transparent isodensity surfaces are also shown for the highest rest-mass density region (with density increasing from gray to red).

improvement of numerical codes and the degree of realism of their physical descriptions could soon lead to a definitive answer.

Another important limiting factor for the interpretation of GRB 170817A is the considerable gap between the relatively small time scales and spatial scales probed by GRMHD merger simulations (up to order ~ 100 ms and ~ 1000 km) and those relevant for the propagation of an incipient jet through the baryon-polluted environment surrounding the merger site ($\gtrsim 1$ s and $\gtrsim 10^5$ km). The ultimate angular structure and energetics of the escaping jet, which are directly related to the prompt and afterglow SGRB emission, are therefore very hard to associate with specific properties of the merging system and a specific launching mechanism. One of the most important challenges to be addressed in the near future is therefore to obtain a self-consistent model that is able to describe the full evolution from the pre-merger stage up to the final escaping jet.

Merger Ejecta and the Kilonova Transient AT 2017gfo

During and after a BNS merger, a relatively large amount of material (up to $\sim 0.1\ M_\odot$) can be ejected, either via dynamical mechanisms associated with the merger process (tidally driven and shock-driven ejecta) or via baryon-loaded winds launched by the (meta)stable massive NS remnant and/or by the accretion disk around the newly formed BH (if any). Depending on the thermodynamical history and composition (in particular the electron fraction Y_e) of each fluid element within the ejecta, the r-process nucleosynthesis takes place and produces a certain amount of heavy elements (i.e., heavier than iron). Later on, the radioactive decay of these elements powers the thermal transient commonly referred to as a kilonova (e.g., Metzger, 2019 and references therein).

For a given ejecta component, the peak luminosity, peak time, and peak frequency (or temperature) of the corresponding kilonova are mainly determined by the ejecta mass, velocity, and opacity (e.g., Grossman et al., 2014). While the mass and velocity depend on the mass ejection mechanism, the opacity is directly related to the nucleosynthesis yields. In particular, high electron fractions ($Y_e \gtrsim 0.25$) typically produce elements up to atomic mass numbers $A \lesssim 140$, maintaining a relatively low opacity of ~ 0.1–$1\ \mathrm{cm}^2/\mathrm{g}$, whereas more neutron-rich ejecta ($Y_e \lesssim 0.25$) allow the production of elements up to $A > 140$ (including the group of lanthanides), which leads to much higher opacities of $\sim 10\ \mathrm{cm}^2/\mathrm{g}$ (e.g., Kasen et al., 2013; Tanaka and Hotokezaka, 2013).

When applied to the kilonova of August 2017, the above picture reveals that the observed transient (AT 2017gfo) was generated by at least two distinct ejecta components (e.g., Kasen et al., 2017)[4], one having mass ≈ 1.5–$2.5 \times 10^{-2}\ M_\odot$, velocity ≈ 0.2–$0.3\ c$, and a relatively low opacity of $\approx 0.5\ \mathrm{cm}^2/\mathrm{g}$, leading to a "blue" kilonova peaking at ~ 1 day after merger, and the other having mass ≈ 4–$6{\times}10^{-2}\ M_\odot$, velocity $\approx 0.1\ c$, and a much higher opacity of $\sim 10\ \mathrm{cm}^2/\mathrm{g}$, leading to a "red" kilonova emerging on a time scale of ~ 1 week. One of the current challenges is to identify the mass ejection mechanisms responsible for these components. In such a quest, numerical relativity simulations of BNS mergers play a pivotal role.

The "red" part of the 2017 kilonova is perhaps the easier of the two to account for. The very large mass and low velocity would exclude dynamical mass ejection and point to a baryon-loaded wind. In particular, the mass expelled by the accretion disk around the BH (i.e., after the collapse of the NS remnant) appears to match the requirements, including a relatively high opacity, or equivalently a low electron fraction, for at least part of the material (e.g., Siegel and Metzger, 2018).

The origin of the "blue" kilonova is more debatable. The ejecta mass is rather high, but then so is the velocity ($v \gtrsim 0.2\ c$). The former still raises doubts over a dynamical ejection, while the latter represents a potential problem for post-merger baryon-loaded winds. The magnetically driven wind from the (meta)stable NS remnant offers a viable solution (Ciolfi and Kalinani, 2020), thanks to the enhanced mass ejection and the simultaneous acceleration due to the magnetic field (as previously suggested, e.g., in Metzger et al., 2018). In this case, neutrino irradiation would also be fundamental for raising the Y_e of the material, limiting the r-process nucleosynthesis, and thus maintaining a low opacity (Metzger et al., 2018). We stress, however, that other viable scenarios exist (e.g., Kawaguchi et al., 2018; Nedora et al., 2019).

Current kilonova models are still affected by several uncertainties around the microphysical parameters, the radiation transport (which is treated with strong approximations), and the mass ejection mechanisms. Nonetheless, we are witnessing rapid theoretical and numerical progress that will keep guiding us toward a more solid interpretation of the observational data.

---

[4] Three-component models were also proposed (e.g., Perego et al., 2017a).

CONCLUDING REMARKS

The growing interest in BNS mergers over the past few decades has recently been boosted by the multimessenger observation of the August 2017 event, GW170817. Among numerous breakthrough results, this BNS merger has provided fundamental confirmations of theoretical predictions, in particular the association with SGRBs, which was already supported by indirect evidence but still unproven, and the production of heavy r-process elements and the related kilonova transients. This success on the theory side certainly strengthens motivation for the development of models and numerical simulations. At the same time, the case of GW170817 has shown that present and near-future observations are likely to contain much more information than we are currently capable of exploiting, making further advancements in our ability to interpret the data more urgent than ever.

AUTHOR CONTRIBUTIONS

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

REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Ackley, K., Adams, C., et al. (2017a). Exploring the sensitivity of next generation gravitational wave detectors. *Class. Quant. Gravity* 34:044001. doi: 10.1088/1361-6382/aa51f4

Abbott, B. P., Abbott, R., Abbott, T. D., Abraham, S., Acernese, F., Ackley, K., et al. (2020). GW190425: observation of a compact binary coalescence with total mass $\sim 3.4\ M_{\odot}$. *Astrophys. J. Lett.* 892:L3. doi: 10.3847/2041-8213/ab75f5

Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., et al. (2017b). A gravitational-wave standard siren measurement of the Hubble constant. *Nature* 551, 85–88. doi: 10.1038/nature24471

Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., et al. (2017c). Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. *Astrophys. J. Lett.* 848:L13. doi: 10.3847/2041-8213/aa920c

Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., et al. (2017d). 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., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., et al. (2017e). Multi-messenger observations of a binary neutron star merger. *Astrophys. J. Lett.* 848:L12. doi: 10.3847/2041-8213/aa91c9

Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., et al. (2019). Properties of the binary neutron star merger GW170817. *Phys. Rev. X* 9:011001. doi: 10.1103/PhysRevX.9.011001

Alexander, K. D., Berger, E., Fong, W., Williams, P. K. G., Guidorzi, C., Margutti, R., 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. Lett.* 848:L21. doi: 10.3847/2041-8213/aa905d

Alexander, K. D., Margutti, R., Blanchard, P. K., Fong, W., Berger, E., Hajela, A., et al. (2018). A decline in the X-ray through radio emission from GW170817 continues to support an off-axis structured jet. *Astrophys. J. Lett.* 863:L18. doi: 10.3847/2041-8213/aad637

Arcavi, I., Hosseinzadeh, G., Howell, D. A., McCully, C., Poznanski, D., Kasen, D., et al. (2017). Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger. *Nature* 551, 64–66. doi: 10.1038/nature24291

Baiotti, L., and Rezzolla, L. (2017). Binary neutron star mergers: a review of Einstein's richest laboratory. *Rep. Prog. Phys.* 80:096901. doi: 10.1088/1361-6633/aa67bb

Barthelmy, S. D., Chincarini, G., Burrows, D. N., Gehrels, N., Covino, S., Moretti, A., et al. (2005). An origin for short γ-ray bursts unassociated with current star formation. *Nature* 438, 994–996. doi: 10.1038/nature04392

Berger, E. (2014). Short-duration gamma-ray bursts. *Ann. Rev. Astron. Astrophys.* 52, 43–105. doi: 10.1146/annurev-astro-081913-035926

Ciolfi, R. (2018). Short gamma-ray burst central engines. *Int. J. Mod. Phys. D* 27:1842004. doi: 10.1142/S021827181842004X

Ciolfi, R. (2020a). Collimated outflows from long-lived binary neutron star merger remnants. *Mon. Not. R. Astron. Soc. Lett.* 495, L66–L70. doi: 10.1093/mnrasl/slaa062

Ciolfi, R. (2020b). The key role of magnetic fields in binary neutron star mergers. *arXiv* 2003.07572.

Ciolfi, R., and Kalinani, J. V. (2020). Magnetically driven baryon winds from binary neutron star merger remnants and the blue kilonova of August 2017. *arXiv* 2004.11298.

Ciolfi, R., Kastaun, W., Giacomazzo, B., Endrizzi, A., Siegel, D. M., and Perna, R. (2017). General relativistic magnetohydrodynamic simulations of binary neutron star mergers forming a long-lived neutron star. *Phys. Rev. D* 95:063016. doi: 10.1103/PhysRevD.95.063016

Ciolfi, R., Kastaun, W., Kalinani, J. V., and Giacomazzo, B. (2019). First 100 ms of a long-lived magnetized neutron star formed in a binary neutron star merger. *Phys. Rev. D* 100:023005. doi: 10.1103/PhysRevD.100.023005

Coulter, D. A., Foley, R. J., Kilpatrick, C. D., Drout, M. R., Piro, A. L., Shappee, B. J., et al. (2017). Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source. *Science* 358, 1556–1558. doi: 10.1126/science.aap9811

Eichler, D., Livio, M., Piran, T., and Schramm, D. N. (1989). Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. *Nature* 340, 126–128. doi: 10.1038/340126a0

Faber, J. A., and Rasio, F. A. (2012). Binary neutron star mergers. *Liv. Rev. Rel.* 15:8. doi: 10.12942/lrr-2012-8

Fox, D. B., Frail, D. A., Price, P. A., Kulkarni, S. R., Berger, E., Piran, T., et al. (2005). The afterglow of GRB050709 and the nature of the short-hard gamma-ray bursts. *Nature* 437, 845–850. doi: 10.1038/nature04189

Gehrels, N., Sarazin, C. L., O'Brien, P. T., Zhang, B., Barbier, L., Barthelmy, S. D., et al. (2005). A short γ-ray burst apparently associated with an elliptical galaxy at redshift z = 0.225. *Nature* 437, 851–854. doi: 10.1038/nature04142

Ghirlanda, G., Salafia, O. S., Paragi, Z., Giroletti, M., Yang, J., Marcote, B., et al. (2019). Compact radio emission indicates a structured jet was produced by a binary neutron star merger. *Science* 363, 968–971. doi: 10.1126/science.aau8815

Goldstein, A., Veres, P., Burns, E., Briggs, M. S., Hamburg, R., Kocevski, D., et al. (2017). An ordinary short gamma-ray burst with extraordinary implications: fermi-GBM detection of GRB 170817A. *Astrophys. J. Lett.* 848:L14. doi: 10.3847/2041-8213/aa8f41

Grossman, D., Korobkin, O., Rosswog, S., and Piran, T. (2014). The long-term evolution of neutron star merger remnants–II. Radioactively powered transients. *Mon. Not. R. Astron. Soc.* 439, 757–770. doi: 10.1093/mnras/stt2503

Hallinan, G., Corsi, A., Mooley, K. P., Hotokezaka, K., Nakar, E., Kasliwal, M. M., et al. (2017). A radio counterpart to a neutron star merger. *Science* 358, 1579–1583. doi: 10.1126/science.aap9855

Just, O., Obergaulinger, M., Janka, H.-T., Bauswein, A., and Schwarz, N. (2016). Neutron-star merger ejecta as obstacles to neutrino-powered jets of gamma-ray bursts. *Astrophys. J. Lett.* 816:L30. doi: 10.3847/2041-8205/816/2/L30

Kasen, D., Badnell, N. R., and Barnes, J. (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., Metzger, B., Barnes, J., Quataert, E., and Ramirez-Ruiz, E. (2017). Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event. *Nature* 551, 80–84. doi: 10.1038/nature24453

Kastaun, W., and Ohme, F. (2019). Finite tidal effects in GW170817: Observational evidence or model assumptions? *Phys. Rev. D* 100:103023. doi: 10.1103/PhysRevD.100.103023

Kawaguchi, K., Shibata, M., and Tanaka, M. (2018). Radiative transfer simulation for the optical and near-infrared electromagnetic counterparts to GW170817. *Astrophys. J. Lett.* 865:L21. doi: 10.3847/2041-8213/aade02

Kawamura, T., Giacomazzo, B., Kastaun, W., Ciolfi, R., Endrizzi, A., Baiotti, L., et al. (2016). Binary neutron star mergers and short gamma-ray bursts: effects of magnetic field orientation, equation of state, and mass ratio. *Phys. Rev. D* 94:064012. doi: 10.1103/PhysRevD.94.064012

Kiuchi, K., Kyutoku, K., Sekiguchi, Y., Shibata, M., and Wada, T. (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

Kumar, P., and Zhang, B. (2015). The physics of gamma-ray bursts and relativistic jets. *Phys. Rep.* 561, 1–109. doi: 10.1016/j.physrep.2014.09.008

Lazzati, D., Perna, R., Morsony, B. J., Lopez-Camara, D., Cantiello, M., Ciolfi, R., 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

Li, L.-X., and Paczyński, B. (1998). Transient events from neutron star mergers. *Astrophys. J.* 507, L59–L62. doi: 10.1086/311680

Lyman, J. D., Lamb, G. P., Levan, A. J., Mandel, I., Tanvir, N. R., Kobayashi, S., et al. (2018). The optical afterglow of the short gamma-ray burst associated with GW170817. *Nat. Astron.* 2, 751–754. doi: 10.1038/s41550-018-0511-3

Margutti, R., Berger, E., Fong, W., Guidorzi, C., Alexander, K. D., Metzger, B. D., 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. Lett.* 848:L20. doi: 10.3847/2041-8213/aa9057

Metzger, B. D. (2019). Kilonovae. *Liv. Rev. Rel.* 23:1. doi: 10.1007/s41114-019-0024-0

Metzger, B. D., Martínez-Pinedo, G., Darbha, S., Quataert, E., Arcones, A., Kasen, D., et al. (2010). Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei. *Mon. Not. R. Astron. Soc.* 406, 2650–2662. doi: 10.1111/j.1365-2966.2010.16864.x

Metzger, B. D., Thompson, T. A., and Quataert, E. (2018). A magnetar origin for the kilonova ejecta in GW170817. *Astrophys. J. Lett.* 856:101. doi: 10.3847/1538-4357/aab095

Mooley, K. P., Deller, A. T., Gottlieb, O., Nakar, E., Hallinan, G., Bourke, S., et al. (2018a). Superluminal motion of a relativistic jet in the neutron-star merger GW170817. *Nature* 561, 355–359. doi: 10.1038/s41586-018-0486-3

Mooley, K. P., Nakar, E., Hotokezaka, K., Hallinan, G., Corsi, A., Frail, D. A., et al. (2018b). A mildly relativistic wide-angle outflow in the neutron-star merger event GW170817. *Nature* 554, 207–210. doi: 10.1038/nature25452

Mösta, P., Radice, D., Haas, R., Schnetter, E., and Bernuzzi, S. (2020). A magnetar engine for short GRBs and kilonovae. *arXiv* 2003.06043.

Narayan, R., Paczynski, B., and Piran, T. (1992). Gamma-ray bursts as the death throes of massive binary stars. *Astrophys. J. Lett.* 395, L83–L86. doi: 10.1086/186493

Nedora, V., Bernuzzi, S., Radice, D., Perego, A., Endrizzi, A., and Ortiz, N. (2019). Spiral-wave wind for the blue kilonova. *Astrophys. J. Lett.* 886:L30. doi: 10.3847/2041-8213/ab5794

Paczynski, B. (1986). Gamma-ray bursters at cosmological distances. *Astrophys. J. Lett.* 308, L43–L46. doi: 10.1086/184740

Perego, A., Radice, D., and Bernuzzi, S. (2017a). AT 2017gfo: an anisotropic and three-component kilonova counterpart of GW170817. *Astrophys. J. Lett.* 850:L37. doi: 10.3847/2041-8213/aa9ab9

Perego, A., Yasin, H., and Arcones, A. (2017b). Neutrino pair annihilation above merger remnants: implications of a long-lived massive neutron star. *J. Phys. G Nucl. Phys.* 44:084007. doi: 10.1088/1361-6471/aa7bdc

Pian, E., D'Avanzo, P., Benetti, S., Branchesi, M., Brocato, E., Campana, S., et al. (2017). Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger. *Nature* 551, 67–70. doi: 10.1038/nature24298

Piran, T. (2004). The physics of gamma-ray bursts. *Rev. Mod. Phys.* 76, 1143–1210. doi: 10.1103/RevModPhys.76.1143

Punturo, M., Abernathy, M., Acernese, F., Allen, B., Andersson, N., Arun, K., et al. (2010). The Einstein telescope: a third-generation gravitational wave observatory. *Class. Quant. Gravity* 27:194002. doi: 10.1088/0264-9381/27/19/194002

Rezzolla, L., Giacomazzo, B., Baiotti, L., Granot, J., Kouveliotou, C., and Aloy, M. A. (2011). The missing link: merging neutron stars naturally produce jet-like structures and can power short Gamma-Ray Bursts. *Astrophys. J. Lett.* 732:L6. doi: 10.1088/2041-8205/732/1/L6

Rosswog, S. (2005). Mergers of neutron star-black hole binaries with small mass ratios: nucleosynthesis, gamma-ray bursts, and electromagnetic transients. *Astrophys. J.* 634, 1202–1213. doi: 10.1086/497062

Ruiz, M., Lang, R. N., Paschalidis, V., and Shapiro, S. L. (2016). Binary neutron star mergers: a jet engine for short gamma-ray bursts. *Astrophys. J. Lett.* 824:L6. doi: 10.3847/2041-8205/824/1/L6

Savchenko, V., Ferrigno, C., Kuulkers, E., Bazzano, A., Bozzo, E., Brandt, S., et al. (2017). INTEGRAL detection of the first prompt gamma-ray signal coincident with the gravitational-wave event GW170817. *Astrophys. J. Lett.* 848:L15. doi: 10.3847/2041-8213/aa8f94

Shibata, M., Suwa, Y., Kiuchi, K., and Ioka, K. (2011). Afterglow of a binary neutron star merger. *Astrophys. J. Lett.* 734:L36. doi: 10.1088/2041-8205/734/2/L36

Shibata, M., and Taniguchi, K. (2011). Coalescence of black hole-neutron star binaries. *Liv. Rev. Rel.* 14:6. doi: 10.12942/lrr-2011-6

Siegel, D. M., Ciolfi, R., and Rezzolla, L. (2014). Magnetically driven winds from differentially rotating neutron stars and X-ray afterglows of short gamma-ray bursts. *Astrophys. J. Lett.* 785:L6. doi: 10.1088/2041-8205/785/1/L6

Siegel, D. M., and Metzger, B. D. (2018). Three-dimensional GRMHD simulations of neutrino-cooled accretion disks from neutron star mergers. *Astrophys. J.* 858:52. doi: 10.3847/1538-4357/aabaec

Smartt, S. J., Chen, T. W., Jerkstrand, A., Coughlin, M., Kankare, E., Sim, S. A., et al. (2017). A kilonova as the electromagnetic counterpart to a gravitational-wave source. *Nature* 551, 75–79. doi: 10.1038/nature24303

Tanaka, M., and Hotokezaka, K. (2013). Radiative transfer simulations of neutron star merger ejecta. *Astrophys. J.* 775:113. doi: 10.1088/0004-637X/775/2/113

Troja, E., Piro, L., van Eerten, H., Wollaeger, R. T., Im, M., Fox, O. D., et al. (2017). The X-ray counterpart to the gravitational-wave event GW170817. *Nature* 551, 71–74. doi: 10.1038/nature24290

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.