Strong post-merger Gravitational Radiation of GW170817-like Events

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Abstract
The post-merger gravitational-wave (GW) radiation of the remnant formed in the binary neutron star (BNS) coalescence has not been directly measured yet. We show in this work that the properties of the BNS involved in GW170817, additionally constrained by PSR J0030+0451, the lower limit on the maximum gravitational mass of nonrotating neutron star (NS), and some nuclear data, are in favor of strong post-merger GW radiation. This conclusion applies to the mergers of Galactic BNS systems as well. Significant post-merger GW radiation is also preferred to improve the consistency between the maximum gravitational mass of the nonrotating NS inferred from GW170817/GRB170817A/AT2017gfo and the latest mass measurements of pulsars. The prominent post-merger gravitational radiation of GW170817-like events is expected to be detectable by advanced LIGO/Virgo detectors in the next decade and then shed valuable light on the properties of the matter in the extremely high density.

Unified Astronomy Thesaurus concepts: Gravitational waves (678); Neutron stars (1108); Gravitational energy (665)

1. Introduction
The mergers of binary neutron stars (BNSs) are prime targets for the second generation gravitational-wave (GW) detectors, such as the advanced LIGO/Virgo and KAGRA (Abbott et al. 2018). During the inspiral the dynamics of neutron stars (NSs) is well described and the gravitational waveforms increase continually in both amplitude and frequency. After the merger the waveforms reflect the oscillations of the formed remnants (either black holes or supramassive NSs) and are much more complicated (in the case of the black hole formation, the waveforms terminate with the ringdown signal). The inspiral signal has a duration of tens of seconds (or even longer) and a low frequency (up to ~1 kHz), which is within the sensitive region of the advanced LIGO/Virgo and KAGRA detectors. The ringdown signal for black holes formed in BNS mergers is instead at frequencies of quite a few kHz, which is usually unmeasurable by the second generation detectors unless the sources are extremely close. The signals from the precollapse remnants are at frequencies lower than the ringdown, but still so high that a detection is challenging (see Baiotti 2019 for a recent review). Such post-merger gravitational waves, anyhow, carry fundamental information on the equation of state (EoS) of the ultra-dense matter as well as the fate of the remnant formed in the BNS merger, and the interest in catching such a signal with the upgrading second generation gravitational detectors is growing. Important progress has been achieved in the numerical simulations of the post-merger gravitational radiation (e.g., Xing et al. 1994; Ruffert et al. 1996; Shibata & Uryū 2000; Damour & Nagar 2010; Hotokezaka et al. 2013; Bernuzzi et al. 2014; Bauswein & Stergioulas 2015;Bernuzzi et al. 2015; Zappa et al. 2018; Baiotti 2019; Bauswein et al. 2019; Most et al. 2019) and dedicated efforts have been made to develop new data analysis methods (e.g., Clark et al. 2016; Yang et al. 2018). An interesting finding of the numerical simulations is that the post-merger gravitational waves carry away in total about 0.8%–2.5% of mass-energy of the BNS system, depending on the properties of the NSs as well as the EoS of the dense matter (Bernuzzi et al. 2016; Zappa et al. 2018).

On 2017 August 17, the advanced LIGO/Virgo discovered the gravitational-wave signal (i.e., GW170817) from the coalescence of a pair of NSs (Abbott et al. 2017a). Very recently, Abbott et al. (2020) reported the detection of a new GW event GW190425 that involves at least one NS (Han et al. 2020). In comparison to GW170817, GW190425 was just detected by LIGO-Livingston and has a much lower signal-to-noise ratio (SNR). The dedicated search in the data of GW170817 found no signal from the post-merger remnant (Abbott et al. 2017b). In this work we evaluate its amount of post-merger GW radiation in two other ways. We find that the properties of the BNSs involved in GW170817, additionally constrained by PSR J0030+0451, the maximum gravitational mass of the nonrotating NS (MTOV) and some nuclear data, are in favor of efficient post-merger GW radiation. We further show that the strong post-merger GW radiation is preferred in improving the consistency among the MTOV inferred from GW170817/GRB170817A/AT2017gfo and the latest mass measurements of pulsars. These two independent pieces of evidence are encouraging and the detection prospect of the post-merger GW signals from GW170817-like events in the full sensitivity run of LIGO/Virgo/KAGRA is found to be promising.

2. Strong Post-merger Gravitational Radiation of GW170817

2.1. Prominent Post-merger Gravitational Radiation Anticipated for the Properties of the BNSs of GW170817

So far, the only way to theoretically quantify the radiated GW energy is to perform numerical relativity simulations. It turns out that κs2, which parameterizes at leading-order the tidal interactions in the general-relativistic two-body Hamiltonian waveforms’ phase and amplitude (Damour et al. 2012), plays a very important role in estimating the GW radiation (Bernuzzi et al. 2015, 2016). The parameter κT2 for a BNS system takes...
the form of $\kappa_2^T = 3(M_A^4M_B\Lambda_A + M_B^4M_A\Lambda_B)/(M_A + M_B)^5$, where $M$ is the gravitational mass, and $\Lambda$ is the dimensionless tidal deformability of an NS, which is related to the quadrupole Love number $k_2$ and the radius $R$ of the NS by $\Lambda = 2/3(Rc^2/GM)^5k_2$ ($c$ is the speed of light and $G$ is the gravitational constant) (Damour & Nagar 2010). In general, the larger energy emissions correspond to smaller values of $\kappa_2^T$, which, in turn, get smaller values for larger masses, more compact NSs and softer EoS. Using a large set of numerical relativity simulations with different binary parameters and input physics, Zappa et al. (2018) found an empirical relation between $\kappa_2^T$ of the BNS system and the reduced gravitational-wave energy $E_{GW,p} = E_{GW,p}/(M_{tot}c^2)$ emitted in the post-merger phase, which reads

$$e_{GW,p}(\kappa_2^T) = \begin{cases} 0.02 & \kappa_2^T \lesssim 63 \\ 0.059 & 63 \lesssim \kappa_2^T \lesssim 73 \\ a(\kappa_2^T)^{1/3} + b & 73 \lesssim \kappa_2^T \lesssim 458 \\ c\kappa_2^T + d & \kappa_2^T \gtrsim 458 \end{cases}$$

(1)

where $M_{tot}$ is the total gravitational mass of the system, and $\nu = M_A M_B/M_{tot}^2$ is the symmetric mass ratio. And the best-fit values are $a = 2.44$, $b = -0.019$, $c = -5.1 \times 10^{-5}$, and $d = 0.038$ (please see the technical note at https://dcc.ligo.org/T1800417/public/ for details). Their result is shown by the dashed-dotted line in Figure 1 and the left low $E_{GW,p}$ region represents the prompt black hole formation scenario. We have incorporated the nonnegligible fitting error of this formula (see the upper panel of Figure 1) in a Monte Carlo way by using the distribution of the residual as done in Kumar & Landry (2019), and the broadened $E_{GW,p}$ results are shown in the upper panel of Figure 2.

In this work, the parameter ranges are for 68% credibility interval unless specifically mentioned. With Equation (1), the amount of the post-merger gravitational radiation can be reasonably/qualitatively evaluated as long as $\kappa_2^T$ (i.e., the EoS) is known. However, various EoS models have been proposed in the literature and it is not possible to be uniquely determined even in the foreseeable future. Fortunately, under the reasonable assumption that all NSs follow the same EoS, their properties can be jointly/reliably constrained with the nuclear data, the GW data, the measured masses, and the estimated radii of some NSs (e.g., Lattimer & Prakash 2016; Abbott et al. 2017; Most et al. 2018; Landry & Essick 2019). The masses of NSs in some binary systems have been accurately measured and there is a robust lower limit on $M_{TOV} \geq 2M_\odot$ (Cromartie et al. 2020; Kandel & Romani 2020). The radii of NSs, however, usually are just evaluated indirectly and suffer from large systematical uncertainties. Thanks to the successful performance of the Neutron Star Interior Composition Explorer, the situation has changed and very recently the first-ever accurate measurement of mass and radius together for PSR J0030+0451, a nearby isolated quickly rotating NS, has been achieved (Miller et al. 2019; Riley et al. 2019), which favor a stiffer EoS than the data of GW170817. Hence, GW170817, PSR J0030+0451, some nuclear data as well as the lower limit on $M_{TOV}$ can be combined to reliably constrain the EoS as well as the bulk properties of NSs. This can be done either in the EoS parameterizing methods (Raaijmakers et al. 2019; Jiang et al. 2020) or the nonparametric approach (Essick et al. 2020; Landry et al. 2020), and the results are well consistent with each other. Here we directly adopt...
Figure 2. Estimated GW energy emitted during the whole post-merger phase. In the upper panel, the solid lines represent the estimated post-merger energy of GW170817 if the fitting error of Equation (1) is not considered, while the dashed lines show the ones including the fitting error. In the lower panel, the $E_{\text{GW},p}$ of all the BNS sources considered in this work are shown, which have taken into account the joint posteriors of three different kinds of EoS parameterization methods and the fitting error of Equation (1). For the two specific GW events, the error considered in the joint result of GW170817 is shown with the thick red dashed–dotted line, while the GW190425 is shown with the solid black line and its PDF is halved for clarity.

The collapse time of the supramassive NS formed in GW170817 has been inferred to be $t_c = 0.98 \pm 0.31 \text{s}$ (Gill et al. 2019), when the uniform rapid rotation of the NS is insufficient to support against collapse. This imposes a constraint on the $M_{\text{TOV}}$ and the most widely quoted limit is $\lesssim 2.17 \, M_\odot$ (e.g., Margalit & Metzger 2017; Shibata et al. 2017; Rezzolla et al. 2018).

Very recently, Shao et al. (2020b) derived an empirical relation among the critical total mass of BNSs ($M_{\text{tot,c}}$), the mass and compactness (denoted by $\zeta_{\text{TOV}} \equiv M_{\text{TOV}}/R_{\text{TOV}} c^2$) of NS in the nonrotation maximum equilibrium configuration, the dimensionless angular momentum of remnant at the onset of collapse ($j_c$) and the total mass lost apart from the remnant core ($m_{\text{loss}}$), which reads

$$M_{\text{tot,c}} \approx M_{\text{TOV}} \left[ 1 + 0.122 \left( \frac{j_c}{j_{\text{cep}}} \right)^2 + 0.040 \left( \frac{j_c}{j_{\text{cep}}} \right)^4 \right] \times \left( 0.798 + 0.971 \zeta_{\text{TOV}} (1 - 0.991 M_{\odot}^{-1} m_{\text{loss}}) + m_{\text{loss}} \right)$$

(2)
where $j_{\text{kep}} \approx 1.24 \zeta_{\text{TOV}}^0$ is the dimensionless angular momentum of NS spinning at Keplerian angular velocity. Supposing that the GW radiation carried away a few percent of the solar mass energy in the post-merger phase, the precollapse remnant is expected to rotate at the mass-shedding limit (Zappa et al. 2018), as assumed in Margalit & Metzger (2017). In such a case, we have $M_{\text{tot,c}} \approx 1.162 M_{\text{TOV}} (0.798 + 0.971 \zeta_{\text{TOV}}) (1-0.091 M_\odot^{-1} m_{\text{loss}}) + m_{\text{loss}}$. At the collapse time ($t_c \sim 1$ s) of the central remnant of GW170817, $m_{\text{loss}}$ consists of two parts, one is the kilonova/macronova outflow with a mass of $m_{\text{fl}} \approx 0.05 \pm 0.01 M_\odot$ (Pian et al. 2017), and the other is the accretion torus with a mass of $0.015-0.134 M_\odot$ (90% confidence level; and the most plausible value is $0.035 M_\odot$, as found in the GRB 170817A/afterglow modeling by Wang et al. 2019). So far, $\zeta_{\text{TOV}}$ is still not directly measurable and here we adopt the joint constraints set in Jiang et al. (2020). Under the assumption that the precollapse remnant was a supramassive NS supported by the rapid uniform rotation (i.e., $M_{\text{tot,c}} = M_{\text{kep}}$), we can evaluate $M_{\text{TOV}} = 2.16^{+0.06}_{-0.06} M_\odot$ (the 68% credibility interval also includes the uncertainties of the EOS insensitive relationships adopted in Shao et al. 2020b) and the probability distribution is shown in Figure 3. So far, the most massive NS is widely believed to be PSR J0740+6620, which has a mass of $2.14^{+0.10}_{-0.09} M_\odot$ (Cromartie et al. 2020), PSR J2215+5135 may be more massive ($M = 2.28 \pm 0.10 M_\odot$; Kandel & Romani 2020), while the measurement method is not as direct/widely accepted as that of PSR J0740+6620. $M_{\text{TOV}}$ should be larger than the gravitational mass of any stable slowly rotating cold NSs. For the inferred $M_{\text{TOV}}(j = j_{\text{kep}})$, such a request is satisfied for PSR J0740+6620 but mildly violated for PSR J2215+5135.

The powerful GW radiation effectively carries away the angular momentum of the merger formed supramassive NS (Shibata et al. 2019). With a stronger GW radiation, the supramassive NS will rotate slower and a higher $M_{\text{TOV}}$ is needed to support against the collapse (e.g., Fan et al. 2013; Breu & Rezzolla 2016, which is also evident in Equation (2)). Note that the inferred $E_{\text{GW,p}}$ has a wide distribution (see Figure 2) and the corresponding constraint on $M_{\text{TOV}}$ will be modified in comparison to the case of $j = j_{\text{kep}}$. We therefore fully reproduce our calculation made in Shao et al. (2020b), adopting the $E_{\text{GW,p}}$ found in Figure 2 (the combined case) and obtain $M_{\text{TOV}} = 2.17^{+0.09}_{-0.12} M_\odot$ ($2.17^{+0.15}_{-0.12} M_\odot$ for the 90% credibility; with the fixed $E_{\text{GW,p}} = 0.07 M_\odot c^2$ we will yield $M_{\text{TOV}} = 2.23^{+0.12}_{-0.11} M_\odot$, which is similar to the mass of PSR J2215+5135). Intriguingly, Landry et al. (2020) found $M_{\text{TOV}} = 2.22^{+0.30}_{-0.20} M_\odot$ (90% credibility) in the nonparametric constraints of NS matter with gravitational and pulsar observations (very similar values have also been reported in Essick et al. 2020). The consistency between our results and those independently found in the nonparametric constraints of NS matter is encouraging and can be taken as an additional support of our current approach. As shown in Figure 3, the combined $E_{\text{GW,p}}$ case has a higher possibility to have $M_{\text{TOV}} \geq 2.3 M_\odot$ than the case of $j = j_{\text{kep}}$ because of the range extending to $E_{\text{GW,p}} \geq 0.07 M_\odot c^2$. If NSs as massive as $\approx 2.3 M_\odot$ have been accurately measured (say, the mass of PSR J2215+5135 has been firmly confirmed) in the future, $E_{\text{GW,p}} \approx 0.07 M_\odot c^2$ (i.e., the post-merger GW radiation of GW170817 reaches the most promising range) will be needed if our current understanding of GW170817/GRB 170817A/AT2017gfo is robust, unless the high temperature effect has played a key role.
in softening the EoS and then triggering the collapse (Shao et al. 2020a).

3. Detection Prospect of the Post-merger Gravitational Radiation of BNS Mergers

GW170817 was detected by advanced LIGO/Virgo in their second observing run. Though the SNR of the event is high, the sensitivity at 2–4 kHz is still insufficient to catch the post-merger GW radiation (Abbott et al. 2017b). The improvements of the sensitivities are underway. In comparison to the O2 run, the sensitivity of the O5 run is expected to increase by a factor of ∼3.3. This enhancement is about 1.5 times better than the initial design sensitivity. Therefore the detection prospect is more promising than that previously estimated with the initial design sensitivity. In Figure 4, the dashed lines indicate the maximum h_{rss} possible for a narrowband GW signal with some fixed energy contents E_{GW,p} under the most optimistic assumption that the whole energy available after merger is radiated in GWs at a certain frequency (see also Abbott et al. 2017b), where the distance of the source is assumed to be the same as GW170817. Even so, the post-merger GW radiation of GW170817-like events is unlikely to be measurable in the upcoming O4 run for the strongest post-merger GW radiation with E_{GW,p} ∼ 0.1 M_c c^2 (see the purple dashed line in Figure 4). A positive detection is plausible in the O5 observing run when the detectors reach their current design sensitivities for two good reasons. First, with a BNS merger rate of ∼10^3 Gpc^{-3} yr^{-1} (note that LIGO-India is expect to join in 2025, which will increase not only the total SNR of the event but also the factor of the duty cycle), we anticipate the detection of an event as close as ∼40 Mpc in the next decade. Second, as shown in the lower panel of Figure 2, except for the lightest and the heaviest BNS systems known so far, the E_{GW,p} values are in favor of efficient post-merger radiation of E_{GW,p} ∼ quite a few × 10^{-2} M_c c^2. Thus the hatched area in Figure 4 should be taken as the fiducial case. Different from the case of GW170817, now we calculate κ_f in a simplified way. Jiang et al. (2020) have obtained Λ as a function of M (see Figure 3 therein; the piecewise method and the spectral method). As long as the gravitational masses of the BNSs are known, it is straightforward to estimate κ_f. While for the nonparametric result, the universal relations in Kumar & Landry (2019) and the posteriors in Landry et al. (2020) are used to calculated the κ_f. In the lower panel of Figure 1, besides the Galactic BNS systems with accurately measured individual masses, we include GW190425, for which the mass information is taken from the website.4 Abbott et al. (2020) speculated the prompt formation of the black hole for GW190425 and here we do find weak post-merger GW radiation of E_{GW,p} ∼ 0.015 ± 0.009 M_c c^2. In the literature, with the dedicated numerical simulations, people have found that for some EoS models the post-merger GW radiation could be detectable for the sources as close as GW170817 supposing the sensitivity can reach a factor of a few times the initial advanced LIGO/Virgo sensitivity (e.g., Clark et al. 2016; Torres-Rivas et al. 2019). Our estimates of E_{GW,p} however, are EoS-insensitive and the detection prospect are consistent with these EoS-dependent numerical evaluation.

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3 https://dcc.ligo.org/public/0161/P1900218/002/SummaryForObservers.pdf

4 https://dcc.ligo.org/LIGO-P2000026/public; the IMRPhenomDNRT low-spin case.
4. Summary

So far, two BNS merger events (GW170817 and GW190425) have been reported by the LIGO scientific collaboration and Virgo collaboration and the measurements are solely for the inspiral signals. The post-merger gravitational waves carry fundamental information on the EoS of the ultra-dense NS matter as well as the fate of the remnant formed in the BNS merger, and have attracted wide attention. The typical frequencies \( \sim 2-4 \text{ kHz} \) of the post-merger signals, however, are out of the most sensitive region of the second generation GW detectors, which explains the absence of such signals in current BNS merger events. Thanks to the rapid progress made in the numerical simulations, an intriguing relation between \( \kappa_2^2 \) and the strength of the post-merger GW radiation has been suggested in the literature (e.g., Bernuzzi et al. 2016; Zappa et al. 2018). We have calculated \( \kappa_2^2 \) of the BNSs involved in GW170817, benefited with the further constraints from PSR J0030+0451, some nuclear data as well as the robust lower limit on the maximum gravitational mass of the nonrotating NSs. With the distributions of \( \kappa_2^2 \) for three parameterization methods considered in this work and the numerical fitting relation, we transform the \( \kappa_2^2 \) to the \( E_{\text{GW},p} \) which is in favor of efficient post-merger GW radiation (see the upper panel of Figure 2). Moreover, we also show that if in the future neutron stars as massive as \( 2.3 M_\odot \) have been accurately measured, the post-merger GW radiation of GW170817 should be within the high end of our inferred distribution (i.e., it is a very efficient post-merger GW radiator) unless new effects/assumptions have been introduced. We finally show that for typical BNS systems, the post-merger GW radiation is expected to be strong (see the lower panel of Figure 2). Together with a BNS merger rate of \( \sim 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1} \), in the O5 run of advanced LIGO/Virgo/KAGRA/LIGO-India, a few events as close as GW170817 are expected and their post-merger GW radiation is detectable. The successful detection would shed valuable light on the physical properties of the ultra-dense matter.

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