FRB 181112 as a Rapidly-Rotating Massive Neutron Star just after a Binary Neutron Star Merger?: Implications for Future Constraints on Neutron Star Equations of State

SHOTARO YAMASAKI,1,2 TOMONORI TOTANI,3,4 AND KENTA KUCHI5,6

1Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel
2The Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
3Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
4Research Center for the Early Universe, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
5Max-Planck-Institut für Gravitationsphysik, Albert-Einstein-Institut, Am Mühlenberg 1, Potsdam-Golm D-14476, Germany
6Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

Submitted to ApJL

ABSTRACT

The light curve of the fast radio burst (FRB) 181112 is resolved into four successive pulses, and the time interval (∼ 0.8 ms) between the first and third pulses coincides with that between the second and fourth pulses, which can be interpreted as a neutron star (NS) spinning at a period of about 0.8 ms. Although this period is shorter than the most rapidly rotating pulsar currently known (1.4 ms), it is typical for a simulated massive NS formed immediately after the coalescence of binary neutron stars (BNS). Therefore, a BNS merger is a good candidate for the origin of this FRB if the periodicity is real. We discuss the future implications that can be obtained if such a periodicity is detected from FRBs simultaneously with gravitational waves (GW). The remnant spin period $P_{\text{rem}}$ inferred from the FRB observation is unique information which is not readily obtained by current GW observations at the post-merger phase. If combined with the mass of the merger remnant $M_{\text{rem}}$ inferred from GW data, it would set a new constraint on the equation of state of nuclear matter. Furthermore, the post-merger quantity $P_{\text{rem}}/M_{\text{rem}}$, or the tidal deformability of the merger remnant, is closely related to the binary tidal deformability parameter $\tilde{\Lambda}$ of NSs before they merge, and a joint FRB-GW observation will establish a new limit on $\tilde{\Lambda}$. Thus, if $\tilde{\Lambda}$ is also well measured by GW data, a comparison between these two will provide further insights into the nature of nuclear matter and BNS mergers.

Keywords: radio continuum: general — gravitational waves — stars: neutron

1. INTRODUCTION

Fast radio bursts (FRBs) are cosmological radio transients with millisecond duration whose origin is enigmatic (Lorimer et al. 2007; Thornton et al. 2013). In the last decade there has been a remarkable increase in our knowledge about FRBs from the observational perspective (Petroff et al. 2019; Cordes & Chatterjee 2019). Identification of the host galaxy with sub-arcsecond localization accuracy for a dozen of FRBs has placed these sources at redshifts between 0.3 and 0.66 (Chatterjee et al. 2017; Bannister et al. 2019; Ravi et al. 2019; Prochaska et al. 2019; Marcote et al. 2020; Bhandari et al. 2020; Heintz et al. 2020), confirming their cosmological origin. While it has been argued that all FRB sources could potentially repeat (e.g., Ravi 2019), some sources, such as FRB 121102 (Spitler et al. 2016), are statistically more active than the others (e.g., Law et al. 2017; Palaniswamy et al. 2018) and intrinsic burst widths for the repeating sources are known to be larger as compared to those for the so-far non-repeating sources (CHIME/FRB Collaboration et al. 2019; Fonseca et al. 2020), supporting the notion of potentially different origins the two.

The spectral and polarimetric properties of FRBs at high time resolution are crucial to understanding their emission mechanisms and local environments (e.g., Farah et al. 2018; Hessels et al. 2019; Nimmo et al. 2020). One of such sources, thus-far non-repeating FRB 181112, was detected in the Commensal Real-time ASKAP Fast Transients (CRAFT) survey at 1.3 GHz, with a duration of 2.1 ms and a fluence of 26 Jy ms, as reported by Prochaska et al. (2019). The burst was localized...
to a star-forming galaxy at redshift $z = 0.48$. Nevertheless, it has a linear polarization at negligible Faraday rotation measure (RM) $\sim 10$ rad m$^{-2}$, which may disfavor an extremely magnetio-ionic environment, such as a supernova remnant. Recently, Cho et al. (2020) carried out a high time (3-ns) resolution analysis of this burst, and found out that the burst is composed of a train of four narrow pulses separated by submilliseconds each. More recently, Day et al. (2020) also found that double-peaked FRBs 190102 and 190611 detected by ASKAP, both share some phenomenological similarities with FRB 181112.

In this Letter, we consider implications of the observations of narrow pulses in FRB 181112. Intriguingly, the time interval between the first and third pulses ($\sim 0.8$ ms) coincides with that between the second and fourth pulses, implying that there would be an underlying neutron star (NS) spinning at extremely short period $\sim 0.8$ ms, and such a fast rotation could be most naturally achieved by a coalescence of binary neutron stars (BNS). In this case, spinning magnetic fields of merging NSs (Totani 2013) or the interaction between the NS magnetospheres (Wang et al. 2016) during the final stage of a BNS merger inspiral can produce an FRB, which would be hidden at 0.5-1 ms after the merger due to the subsequent mass ejection (Yamasaki et al. 2018). Therefore, if our interpretation of the underlying periodicity between sub-pulses of FRB 181112 is correct, it would provide strong support to the BNS-merger origin for this FRB. We also examine the idea that future co-detection of the gravitational wave (GW) from such FRBs provide the completely new information on the NS that is complementary to the relatively poor sensitivity of current GW detectors right after the BNS merger.

This Letter is organized as follows. In §2, we present our interpretation of the temporal properties of FRB 181112 on the basis of BNS merger model for FRBs. In §3, possible constraints on the NS equations of state is presented, followed by discussion in §4. Throughout this work, we use a geometrical unit with $c = 1$, where $c$ and $G$ are the speed of light and the gravitational constant, respectively.

2. FRB 181112 FROM BNS MERGER?

2.1. Interpretation of Four Narrow Pulses

According to Cho et al. (2020), the singly-detected FRB 181112 consists of four narrow pulses with signal-to-noise ratio (S/N) of 220, 5, 28, and 8 respectively, arriving at times $t_1 = 0$ ms, $t_2 = 0.48 \pm 0.01$ ms, $t_3 = 0.808 \pm 0.004$ ms, and $t_4 = 1.212 \pm 0.002$ ms, where $t_i$ refers to the peak of the profile of pulse $i$. Although no significant periodicity cannot be claimed because of the small number of pulses, the interval $t_{31} = 0.808$ ms between the pulses 1 and 3 is interestingly close to $t_{42} = 0.732$ ms between the pulses 2 and 4, implying a tempting possibility of a periodicity around 0.8 ms (Cho et al. 2020). This is consistent with the duration (width) of an individual pulse $\leq 0.1$ ms and negligible temporal pulse broadening due to scattering $\sim 20$ $\mu$s. Assuming that the four pulses randomly distribute within the time window of $2P \sim 1.6$ ms, we estimate by a simple Monte Carlo method that there is a non-negligible $\lesssim 18\%$ probability for the $|t_{31} - t_{42}|$ to be less than the observed difference 0.076 ms by chance alone.

Though this chance probability alone does not allow us to claim the existence of periodicity with a high level of confidence, there is other circumstantial evidence to support the hypothesis that pulses 1 and 3 are of the same origin (see, e.g., Table 1 and Figure 1 of Cho et al. 2020). First, pulses 1 and 3 have similarly high S/N, which is in contrast to the low S/N of weak pulses 2 and 4. Secondly, the Faraday rotations were measured only in pulses 1 and 3 with their polarization angles being consistent with each other within 20°, suggesting that a similar magnetic field geometry may have been achieved in these two pulses. Furthermore, there is a potential similarity in the time-frequency structures of pulses. The dynamic spectra of pulses 1 and 3 extend across the observing band up to $\sim 1450$ MHz, whereas pulses 2 and 4 possibly have a spectral cutoff at around $\lesssim 1300$ MHz (see Figure 2 of Cho et al. 2020). Therefore, these data might support the interpretation of the 0.8 ms periodicity, in which case the four pulses are emitted over two rotational periods.

If the submillisecond periodicity is real, it is reasonable to regard it as the rotation of an underlying compact star, such as a NS. Lattimer & Prakash (2007) showed that the minimum spin period for a uniformly rotating NS with non-rotating mass $M$ and radius $R$ in fully relativistic calculations employing realistic hadronic EOSs is approximated as $P_{\text{min}} \approx (0.96 \pm 0.03) (M/\text{M}_\odot)^{1/2} (R/10 \text{ km})^{3/2}$ ms, which applies to an arbitrary NS mass as long as it is not close to the maximum non-rotating mass (whereas for the maximum mass configuration, the coefficient reduces to 0.83). That is, for $M \gtrsim 1.4 M_\odot$ star with its radius $R \approx 10$ km, the minimum spin period would be limited to $P_{\text{min}} \lesssim 0.8$ ms regardless of EOS. Thus, most NS EOSs, at least in theory, allow for short spin period at $P = 0.8$ ms seen in FRB 181112.

2.2. The Origin of Most Rapidly Spinning NS

What is the possible progenitor of a NS with such a short spin period? The most common channel for the formation of NSs is core collapse supernova (CCSNe). Current evolutionary models of progenitors combined with numerical simulations of core collapses and explosions (e.g., Spruit & Phinney 1998; Heger et al. 2000, 2005; Thompson et al. 2005; Ott et al. 2006; Nakamura et al. 2014) show that the spin period of a newborn NS can be as small as a few milliseconds only if the spin rate of the progenitor is sufficiently high. Meanwhile, the initial spins of pulsars are not well constrained by observations but, most likely, they lie in the vicinity of tens to hundreds of milliseconds (e.g., Narayan 1987; Lorimer
et al. 1993; Kaspi & Helfand 2002; Faucher-Giguère & Kaspi 2006; Miller & Miller 2015). The most rapidly rotating pulsar currently known is J1748–2446ad with \( P = 1.4 \) ms (Hessels et al. 2006), which however is not an isolated pulsar but a recycled one in a binary system, and so far no submillisecond pulsars have been found, despite vigorous pulsar explorations (e.g., Lorimer 2008).

Moreover, depending on the mass of SN ejecta, it takes about 10–100 years for the surrounding environment to become transparent to the radio waves (e.g., Murase et al. 2016; Kashiya et al. 2017; Metzger et al. 2017). Thus, even though the remnant NS from a CCSN is born rapidly rotating, with an initial spin period of submilliseconds, it would have significantly spun down by the time when an FRB produced by its activity could be observed, unless the initial NS magnetic field is too low and/or the NS angular momentum significantly increases due to a fallback accretion (e.g., Shigeyama & Kashiyama 2018). Therefore, the explanation of the submillisecond rotation by CCSNe requires fine tuning of the parameters.

Another possible channel for NS formation is the coalescence of binary neutron stars (BNSs). Such a remnant after the merger, called massive NS, would start out rapidly rotating and gradually slow down through emission of gravitational and electromagnetic radiations (Shibata & Hotokezaka 2019) mass and also on the NS equations of state (EOS), it could survive for hundreds of milliseconds and eventually collapse to a black hole (Hotokezaka et al. 2013) or it could actually remain stable indefinitely (Shibata & Hotokezaka 2019). Since the remnant NS inherits the large kinetic energy \( \sim 10^{53} \) erg of the binary orbital motion, its initial spin period is typically about 0.5–1.0 ms, which is suggested by the numerical relativity simulations with the plausible value of the binary mass of 2.5–2.7\( M_\odot \) (Radice et al. 2018). In this respect, the explanation of the \( P = 0.8 \) ms rotation seen in FRB 181112 would be most naturally interpreted as the spin rate of the BNS merger remnant without fine tuning of parameters.

Furthermore, in the framework of BNS merger scenarios for FRBs (Totani 2013; Wang et al. 2016), the rotational energy budget available for FRB emission dramatically increases until the moment of coalescence. Meanwhile, the dynamical ejecta begin to screen the radio emission at times about 0.5–1 ms after the merger (Yamasaki et al. 2018), which may limit the maximum duration of an FRB and thus one will not “see” the subsequent FRB sub-pulses if any. Therefore, we conclude that FRB 181112 could be most naturally interpreted as the repeated radio emissions from the remnant NS around the moment of coalescence that have survived the absorption due to the subsequent expansion of dynamical ejecta.

3. FUTURE IMPLICATIONS ON NEUTRON STAR EQUATIONS OF STATE

While the possible presence of submillisecond periodicity in FRB 181112 strengthens the support for the BNS merger origin for this FRBs as shown in §2, the most unambiguous confirmation is only achieved by detecting the GW emission simultaneously with an FRB (Totani 2013; Zhang 2014; Yamasaki et al. 2018; Wang et al. 2020b). In this section, we discuss the future implications of a simultaneous detection of an FRB 181112-like FRB and the associated GW for NS matter EOSs. For these purposes we make use of the latest numerical-relativity simulations of BNS mergers (§3.1).

On this basis, we demonstrate some relations among key BNS-merger properties and show how FRB and GW observations can be combined with such relations to constrain the NS properties (§3.2 and §3.3).

3.1. Simulation Data and Physical Quantities of Interest

We use the numerical-relativity simulations of BNS mergers (Kiuchi et al. 2017, 2020) performed with five phenomenological EOSs (polytropic EOSs for dense nuclear matter with broken power law, see Read et al. 2009), which produce a wide range of spherical NS radii \( R_{1.35} = 10.96–13.69 \) km for a 1.35 \( M_\odot \) star. As shown below, our purposes are to demonstrate the qualitative dependence of the remnant spin period on the remnant mass and to obtain the relationship between compactnesses before and after the merger. Therefore, a choice of relatively simple EOSs is sufficient. Here we try the models with total mass \( m_{\text{tot}} = 2.50–2.73 \) \( M_\odot \) and mass ratio \( q = m_1/m_2 = 0.7–1.0 \), where \( m_1 + m_2 = m_{\text{tot}} \). The primary quantities of our interest are the minimum spin period of the remnant (\( P_{\text{rem}} \)), the remnant mass (\( M_{\text{rem}} \)), and the binary tidal deformability parameter (\( \Lambda \)), which are extracted from the simulations as follows.

In general, the remnant is initially rotating differentially, which is characterized by a slowly rotating core surrounded by a rapidly rotating outer layer, and depending on the magnetorotational instabilities and/or the neutrino cooling, the rotational profile evolves into Keplerian one (e.g., Shibata et al. 2005; Fujibayashi et al. 2020). Namely, the rotational profile is highly unstable (hence not appreciable) around the time of merger. Thus, we extract the minimum spin period by examining the location of the peak in the angular velocity profile along the equator of the merged NS remnant (or orbital plane) at about 10–15 ms after the merger. The errors in \( P_{\text{rem}} \) arising from simulations are estimated to be \( \lesssim 6\% \). We approximate the remnant mass by the total mass of the NSs for simplicity (i.e., \( M_{\text{rem}} \sim m_{\text{tot}} \)). Other potential systematic uncertainties in \( P_{\text{rem}} \) and \( M_{\text{rem}} \) will be discussed in §4. This

\(^{1}\) If the remnant NS survives for long time (\( \geq 1 \) year) after the merger, its rotational or magnetic activity may produce repeating FRBs (Yamasaki et al. 2018, see also Margalit et al. 2019; Wang et al. 2020b).
The simulation with softest EOS (corresponding to \( R_{\text{1.35}} = 10.96 \) km) with high total mass \( M_{\text{rem}} \) is used to set the simulation uncertainties arising from the differential rotation of the remnant, which are set to be the simulation uncertainties. The vertical error bars are coming from the uncertainty of the total mass of the NSs. The post-merger spin period of the remnant NS \( P_{\text{rem}} \) is used to see a high-time-resolved FRB with submillisecond periodicity. In this case, \( P_{\text{rem}} \) and \( R_{\text{rem}} \) are both measurable by the FRB and GW observations, respectively. For instance, let us consider a hypothetical FRB-GW detection by taking \( P_{\text{rem}} \) from FRB 181112 and \( M_{\text{rem}} \) from GW170817. Then, one can constrain the allowed parameter space on the \( P_{\text{rem}}-M_{\text{rem}} \) plane (see the area where the horizontal and vertical shaded regions intersect in Figure 1). This demonstrates that the simultaneous measurement of \( P_{\text{rem}} \) and \( M_{\text{rem}} \) would provide an important constraint on the EOS.

3.3. Period/Mass-Tidal Deformability Relation

Additionally, we consider a case where the tidal deformability (as well as \( M_{\text{rem}} \)) is measured by the GW observations in a case of detecting a neutron star inspiral. The binary tidal deformability, \( \tilde{\Lambda} \), can be written as (Flanagan & Hinderer 2008; Hinderer 2008)

\[
\tilde{\Lambda} = \frac{8}{15} \left[ \left( 1 + 7 \eta - 31 \eta^2 \right) (\Lambda_1 + \Lambda_2) \\
+ \sqrt{1 - 4 \eta (1 + 9 \eta - 11 \eta^2 ) (\Lambda_1 - \Lambda_2)} \right],
\]

where \( \eta = m_1 m_2 / m_{\text{tot}}^2 \) is the symmetric mass ratio and \( \Lambda_i \) \((i = 1, 2)\) is the tidal deformability of each star, defined as

\[
\Lambda_i \equiv \frac{2}{3} k_2^{(i)} \left( \frac{R_i}{m_i} \right)^5,
\]

where \( k_2^{(i)} \) is the quadrupolar Love numbers of each NS. For simplicity, we consider near-equal-mass NSs with \( \eta \sim 1/4 \), in which case \( \tilde{\Lambda} \sim \Lambda_i \). As shown in Figure 2, one can see that the remnant quantity \( P_{\text{rem}} / M_{\text{rem}} \) is closely related to the binary tidal deformability by the relation

\[
\log_{10} \left( \frac{P_{\text{rem}}}{\text{ms}} \right) \left( \frac{M_{\odot}}{M_{\text{rem}}} \right) \approx a_0 + a_1 \tilde{\Lambda}^{1/5},
\]

where \( a_0 = -1.25^{+0.08}_{-0.08} \) and \( a_1 = 0.18^{+0.02}_{-0.02} \) are numerical coefficients with errors of 1-\( \sigma \). This may be qualitatively understood as follows. By assuming that the remnant has a Keplerian rotation, \( P_{\text{rem}} / M_{\text{rem}} \propto (R_{\text{rem}} / M_{\text{rem}})^{3/2} \propto C_{\text{post}}^{-3/2} \), where \( C_{\text{post}} \) is the compactness of the remnant NS. Meanwhile, the NSs’ tidal deformability is related to the compactness of NSs before the merger \( C_{\text{pre}} \) as \( \tilde{\Lambda}^{1/5} \sim C_{\text{pre}}^{1/5} \). Namely, each quantity could be expressed in terms of compactness parameter. Therefore, the clear \( P/M-\tilde{\Lambda}^{1/5} \) correlation in Eq. (3) may imply the existence of hidden relationship between \( C_{\text{pre}} \) and \( C_{\text{post}} \), which could be only investigated through numerical-relativity simulations.

Given the remnant spin period and mass inferred by FRB and GW observations, respectively, one can see that Eq. (3)

---

3 This is qualitatively similar to the so-called “approximate” universal relations” between the post-merger gravitational wave frequency and tidal deformability (e.g., Bauswein et al. 2012; Read et al. 2013; Bernuzzi et al. 2015; Rezzolla & Takami 2016; Zappa et al. 2018; Kiuchi et al. 2020)

3 A slightly different relationship between the binary tidal deformability and the compactness parameter \( \tilde{\Lambda} \propto C^{-6} \) has also been proposed (De et al. 2018; De et al. 2018). Yet, this barely affects our conclusions.
will provide a constraint on the tidal deformability $\tilde{\Lambda}_{\text{FRB}}$, which is completely independent from that directly measured from the inspiral GW $\tilde{\Lambda}_{\text{GW}}$. For instance with a hypothetical FRB-GW detection (taking $P_{\text{rem}}$ from FRB 181112 and $M_{\text{rem}}$ from GW170817), one would obtain $\tilde{\Lambda}_{\text{FRB}} \sim 600 - 1000$. This is actually consistent with the tidal deformability directly measured from the GW170817 $100 \leq \tilde{\Lambda}_{\text{GW}} \leq 800$ (Abbott et al. 2017). We note that the upper limit on the $\tilde{\Lambda}_{\text{GW}}$ is robustly set by the GW analysis, whereas the lower limit is rather dependent on the prior physical information about the NSs. In contrast, as our method of using $P/M - \tilde{\Lambda}^{1/5}$ relation provides a constraint on $\tilde{\Lambda}_{\text{FRB}}$ (hence on NS radii) with an error bar, this would be qualitatively different estimate and thus of great importance. The error in $\tilde{\Lambda}_{\text{FRB}}$ is subject to the accuracy of the FRB and GW observations ($P_{\text{rem}}$ and $M_{\text{rem}}$) and the variance of $P_{\text{rem}}/M_{\text{rem}} - \tilde{\Lambda}^{1/5}$ relation (see §4).

Curiously, even the possible disagreement between $\tilde{\Lambda}_{\text{FRB}}$ and $\tilde{\Lambda}_{\text{GW}}$ may allow us to test whether the empirical relation in Eq. (3), derived solely from numerical relativity simulations, actually holds. A phase transition from normal nuclear matter to quark matter that can take place inside the NSs around the moment of coalescence might modify the BNS merger process, and the tight correlation between $P_{\text{rem}}/M_{\text{rem}}$ and $\tilde{\Lambda}$ obtained for pure nucleonic stars (as done in this work) may not persist anymore (Bauswein et al. 2019). For instance, sharp phase transitions lead to the smaller tidal deformabilities and also induce discontinuities in the relation between tidal deformability and mass (Han & Steiner 2019; Nandi & Pal 2020). Consequently, such phase transitions would lead to a deviation of $\Lambda_{\text{FRB}} - \Lambda_{\text{GW}}$ relation from that shown in Figure 2.

4. SUMMARY AND DISCUSSION

In this letter, we investigated the possibility that the separation among the sub-pulses in FRB 181112 could represent the rotation period of an underlying NS, and the extremely short period of about $0.8$ ms could be a strong evidence for a BNS merger. Base on this picture, we have shown that such a high spin rate inferred from a high time-resolved FRB would offer a unique opportunity to study the nature of the BNS merger remnant, particularly if co-detected with GW. First of all, since the information on the remnant spin pe-
period $P_{\text{rem}}$ is not yet readily available with the current GW observation, the newly proposed method of detecting it via the high time-resolved FRBs is complementary. Moreover, if combined with the remnant NS mass $M_{\text{rem}}$ inferred from GW observation, it would place a new constraint on the nuclear matter EOS. Our numerical relativity simulation suggests that the post-merger quantity $P_{\text{rem}}/M_{\text{rem}}$, or the tidal deformability of the merger remnant, has a tight correlation with the binary tidal deformability parameter $\tilde{\Lambda}$ of NSs before they merge. Given this empirical relation, a joint FRB-GW observation will establish a new limit on $\tilde{\Lambda}$. Therefore, if $\tilde{\Lambda}$ is also well measured by GW data, a comparison between these two will provide further insights into our understanding of nuclear matter and BNS merger process.

Besides the errors related to the simulation described in §3, there may be additional systematic uncertainties in $M_{\text{rem}}$ and $P_{\text{rem}}$ that would also propagate to $P_{\text{rem}}/M_{\text{rem}}$ (Figure 1) and $P_{\text{rem}}/M_{\text{rem}}\cdot\Lambda^{1/3}$ (Figure 2 and Eq. [3]) relations. In this work, we approximated the mass of the remnant NS by the total mass of the pre-merger binary system. Meanwhile, a number of simulations have shown that the post-merger system generally consists of a central core with differential rotation (corresponding to the remnant NS considered here) and an accretion disk that uniformly rotates around it (e.g. Shibata & Hotokezaka 2019). In this context, the spatial extent of the remnant NS (or the total mass) is not a well-defined concept, but simulations using typical binary masses of $2.5–2.7\,M_\odot$ suggest that, depending on the mass of the disk, the uncertainty in $M_{\text{rem}}$ is up to $0.1–0.3\,M_\odot$ (Fujibayashi et al. 2020), which translates into a fractional error in $M_{\text{rem}}$ of $\lesssim 10\%$.

Similarly, $P_{\text{rem}}$ may have multiple systematic uncertainties. First, the spin period is not a gauge-independent quantity in general relativity, and therefore the derived relations could in principle change when choosing different simulation setups. Nevertheless, by comparing the frequency of the dominant quadrupole mode of GW radiation, which is gauge invariant, with the remnant spin frequency we confirm that the effect of gauge is negligible (see Appendix A). Secondly, since our simulation covers only a limited mass range, we need a more comprehensive study to evaluate the variance of those relations. Third, as the rotational profile of the remnant is time-dependent, the minimum spin period may change depending on when one extracts it from a simulation. Finally, the shock-wave heating during the coalescence, which depends on a BNS model, may also affect the rotational profile. Since this work is the very first step toward probing BNS merger EOS by means of FRBs, we leave the exploration of these possibilities for future works.

Based on the BNS merger models (Totani 2013; Yamasaki et al. 2018) and also hinted by the observation of FRB 181112 (Cho et al. 2020), we predict a unique population of non-repeating FRBs having multiple sub-pulses with submillisecond periodicity. The full duration of such FRBs may be determined by the dynamical timescale of ejecta that would hide the radio waves at times of about 0.5–1 ms after the coalescence (Yamasaki et al. 2018). As a result, no subsequent FRB sub-pulse would be observed.

The FRB 121002 (Champion et al. 2016) is the first FRB sample that clearly shows double components. However, due to its somewhat large separation between two peaks 2.4 ± 0.4 ms, it cannot be a strong evidence for a BNS merger. Meanwhile, recently discovered double-peaked FRBs 190102 and 190611 (Day et al. 2020) could be good candidates for this population. The peak separations for FRBs 190102 and 190611 are about 0.5 ms and 1 ms, respectively with small scattering timescales (0.04 ms and 0.18 ms, respectively) and the rotation measure for two sub-pulses in each burst are comparable, sharing many phenomenological similarities to FRB 181112 (Day et al. 2020). Further in-depth modelling of the radio emission signature from merging BNSs (e.g., Palenzuela et al. 2013; Carrasco & Shibata 2020; Most & Philippov 2020; Wada et al. 2020) as well as their possible connection to FRBs will be required to see if such models can account for the sub-pulse separations observed.

A population of FRBs that is similar to FRB 181102 will be found by ongoing (ASKAP) and future (e.g., SKA) high-time resolution surveys. Also, there is a fascinating possibility that GWs and radio waves can be accurately observed simultaneously by forecasting the BNS merger with the space-based detector DEci-hertz Interferometer Gravitational wave Observatory (DECIGO, Kawamura et al. 2006; Sato et al. 2017). Ultimately, in the era of third-generation detectors, such as the Einstein Telescope (Hild et al. 2011) and the Cosmic Explorer (Abbott et al. 2017), post-merger GWs and FRBs similar to FRB 181102 will be detected simultaneously, enabling a direct comparison between the remnant spin periods obtained by FRBs and GWs.

ACKNOWLEDGMENTS

SY gratefully acknowledges the support from the Institute for Cosmic Ray Research during the course of this work. TT was supported by JSPS/MEXT KAKENHI Grant Numbers 18K03692 and 17H06362. KK was supported by 18H01213. The numerical computation was performed on Cray XC50 at cfca of National Astronomical Observatory of Japan, Oakforest-PACS at Information Technology Center of the University of Tokyo, and on Cray XC40 at Yukawa Institute for Theoretical Physics, Kyoto University.
A. ASSESSMENT OF THE MINIMUM SPIN PERIOD EXTRATION

In this work, we extract the minimum spin period of the remnant \( P_{\text{rem}} = 2\pi/\Omega_{\text{max}} \) from the simulation by directly examining the peak \( \Omega_{\text{max}} \) in the angular velocity profile of the remnant after the merger (§3.1). However, one concern is that \( P_{\text{rem}} \) is not a gauge-invariant quantity and is calculated purely by a Newtonian method. In order to assess the possible gauge dependence of \( \Omega_{\text{max}} \), we compare it with the gauge-invariant quantity, the peak in angular frequency space of the post-merger GW spectrum \( \Omega_{\text{GW,peak}} \), which is often interpreted as twice the spin frequency of fundamental quadrupole oscillation mode (f-mode) of the remnant NS. Since there is no detailed perturbative calculation of the f-mode frequency for a realistic merged remnant as background (but see e.g., Krüger et al. 2010 for calculations under ideal differentially-rotating background models), it is not yet clear whether the customary \( \Omega_{\text{GW,peak}} \approx 2\Omega_{\text{max}} \) relation actually holds. Nevertheless, some numerical relativity simulations suggest a relationship between \( \Omega_{\text{GW,peak}} \) and \( 2\Omega_{\text{max}} \) (Hanauske et al. 2017). Figure 3 compares \( 2\Omega_{\text{max}} \) calculated from the angular velocity profile with \( \Omega_{\text{GW,peak}} \) derived from the simulation by a relativistic method using the Weyl scalar (Yamamoto et al. 2008). Clearly, there is an almost linear correlation between them (with a slope of 0.98 ± 0.07 with errors of 1-\( \sigma \)). This shows that the influence of the gauge is negligible and \( \Omega_{\text{max}} \) (or \( P_{\text{rem}} \)) is a sufficiently good physical quantity that represents the minimum spin period of the remnant NS.

**REFERENCES**

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Phys. Rev. Lett., 119, 161101, doi: 10.1103/PhysRevLett.119.161101
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Classical and Quantum Gravity, 34, 044001, doi: 10.1088/1361-6382/aa51f4
Bauswein, A., Bastian, N.-U. F., Blaschke, D. B., et al. 2019, Science, 365, 565, doi: 10.1126/science.aaw5903
Bauswein, A., Janka, H.-T., Hebeler, K., & Schwenk, A. 2012, Phys. Rev. D, 86, 063001, doi: 10.1103/PhysRevD.86.063001
Bernuzzi, S., Dietrich, T., & Nagar, A. 2015, PhRvL, 115, 091101, doi: 10.1103/PhysRevLett.115.091101
Bhandari, S., Bannister, K. W., Lenc, E., et al. 2020, arXiv e-prints, arXiv:2008.12488.
Champion, D. J., Petroff, E., Kramer, M., et al. 2016, MNRAS, 460, L30, doi: 10.1093/mnrasl/slw069
Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Nature, 541, 58, doi: 10.1038/nature20797
CHIME/FRB Collaboration, Andersen, B. C., Bandura, K., et al. 2019, ApJL, 885, L24, doi: 10.3847/2041-8213/ab4a80
Cho, H., Macquart, J.-P., Shannon, R. M., et al. 2020, ApJL, 891, L38, doi: 10.3847/2041-8213/ab7824
Cordes, J. M., & Chatterjee, S. 2019, ARA&A, 57, 417, doi: 10.1146/annurev-astro-091918-104501
Day, C. K., Deller, A. T., Shannon, R. M., et al. 2020, arXiv e-prints, arXiv:2005.13162.
De, S., Finstad, D., Lattimer, J. M., et al. 2018, PhRvL, 121, 091102, doi: 10.1103/PhysRevLett.121.091102
De, S., Finstad, D., Lattimer, J. M., et al. 2018, Phys. Rev. Lett., 121, 259902, doi: 10.1103/PhysRevLett.121.259902
Farah, W., Flynn, C., Bailes, M., et al. 2018, MNRAS, 478, 1209, doi: 10.1093/mnras/sty1122
Shibata, M., Taniguchi, K., & Uryū, K. 2005, PhRvD, 71, 084021, doi: 10.1103/PhysRevD.71.084021
Shigeyama, T., & Kashiyama, K. 2018, PASJ, 70, 107, doi: 10.1093/pasj/psy108
Spitler, L. G., Scholz, P., Hessels, J. W. T., et al. 2016, Nature, 531, 202, doi: 10.1038/nature17168
Spruit, H., & Phinney, E. S. 1998, Nature, 393, 139, doi: 10.1038/30168
Thompson, T. A., Quataert, E., & Burrows, A. 2005, ApJ, 620, 861, doi: 10.1086/427177
Thornton, D., et al. 2013, Science, 341, 53, doi: 10.1126/science.1236789
Totani, T. 2013, PASJ, 65, L12, doi: 10.1093/pasj/65.5.L12
Wada, T., Shibata, M., & Ioka, K. 2020, arXiv e-prints, arXiv:2008.04661. https://arxiv.org/abs/2008.04661
Wang, F. Y., Wang, Y. Y., Yang, Y.-P., et al. 2020a, ApJ, 891, 72, doi: 10.3847/1538-4357/ab74d0
Wang, J.-S., Yang, Y.-P., Wu, X.-F., Dai, Z.-G., & Wang, F.-Y. 2016, ApJL, 822, L7, doi: 10.3847/2041-8205/822/1/L7
Wang, M.-H., Ai, S.-K., Li, Z.-X., et al. 2020b, ApJL, 891, L39, doi: 10.3847/2041-8213/ab7a1b
Yamamoto, T., Shibata, M., & Taniguchi, K. 2008, PhRvD, 78, 064054, doi: 10.1103/PhysRevD.78.064054
Yamasaki, S., Totani, T., & Kiuchi, K. 2018, PASJ, 70, 39, doi: 10.1093/pasj/psy029
Zappa, F., Bernuzzi, S., Radice, D., Perego, A., & Dietrich, T. 2018, Phys. Rev. Lett., 120, 111101, doi: 10.1103/PhysRevLett.120.111101
Zhang, B. 2014, ApJL, 780, L21, doi: 10.1088/2041-8205/780/2/L21