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Search for Post-Merger Gravitational Waves From the Remnant of the Binary Neutron Star Merger GW170817

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SEARCH FOR POST-MERGER GRAVITATIONAL WAVES FROM THE REMNANT OF THE BINARY NEUTRON STAR MERGER GW170817

The LIGO Scientific Collaboration and The Virgo Collaboration

ABSTRACT

The first observation of a binary neutron star coalescence by the Advanced LIGO and Advanced Virgo gravitational-wave detectors offers an unprecedented opportunity to study matter under the most extreme conditions. After such a merger, a compact remnant is left over whose nature depends primarily on the masses of the inspiralling objects and on the equation of state of nuclear matter. This could be either a black hole or a neutron star (NS), with the latter being either long-lived or too massive for stability implying delayed collapse to a black hole. Here, we present a search for gravitational waves from the remnant of the binary neutron star merger GW170817 using data from Advanced LIGO and Advanced Virgo. We search for short ($\lesssim 1\,\mathrm{s}$) and intermediate-duration ($\lesssim 500\,\mathrm{s}$) signals, which includes gravitational-wave emission from a hypermassive NS or supramassive NS, respectively. We find no signal from the post-merger remnant. Our derived strain upper limits are more than an order of magnitude larger than those predicted by most models. For short signals, our best upper limit on the root-sum-square of the gravitational-wave strain emitted from 1–4 kHz is $h_{\mathrm{rss}}^{50\%} = 2.1 \times 10^{-22}\,\mathrm{Hz}^{-1/2}$ at 50% detection efficiency. For intermediate-duration signals, our best upper limit at 50% detection efficiency is $h_{\mathrm{rss}}^{50\%} = 8.4 \times 10^{-22}\,\mathrm{Hz}^{-1/2}$ for a millisecond magnetar model, and $h_{\mathrm{rss}}^{50\%} = 5.9 \times 10^{-22}\,\mathrm{Hz}^{-1/2}$ for a bar-mode model. These results indicate that post-merger emission from a similar event may be detectable when advanced detectors reach design sensitivity or with next-generation detectors.

1. INTRODUCTION

On August 17, 2017 12:41:04.4 UTC, the two detectors of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Advanced Virgo detector observed GW170817, the gravitational wave (GW) signal from the coalescence of two compact objects, almost certainly neutron stars (NSs) (Abbott et al. 2017a). Supporting this hypothesis were electromagnetic counterparts observed across the spectrum (Abbott et al. 2017b,c). Thanks to its relatively close proximity to Earth, with 90% credible intervals of 40^{+8}_{-14} Mpc as measured by the GW data analysis (Abbott et al. 2017a) and $43.8^{+2.9}_{-6.9}$ Mpc as measured with electromagnetic observations (Abbott et al. 2017d), GW170817 offers the first opportunity to study the nature of the remnant leftover from a binary NS merger using GW observations.

The merger of two NSs can have four possible outcomes: (i) The prompt formation of a black hole (BH), (ii) the formation of a hypermassive NS that collapses to a BH in $\lesssim 1$ s, (iii) the formation of a supramassive NS that collapses to a BH on timescales of $\sim 10 - 10^4$ s, or (iv) the formation of a stable NS. The specific outcome of any merger depends on the progenitor masses, with the two NSs that merged in GW170817 having a total mass between 2.73 and 3.29 $M_\odot$ (using the high-spin priors) (Abbott et al. 2017a), and also on the NS equation of state. We present a broad search for both short ($\lesssim 1$ s) and intermediate ($\lesssim 500$ s) duration GW signals potentially emitted from post-merger remnants in scenarios (ii), (iii) and (iv). We find no evidence for a statistically significant signal and set upper limits on possible GW strain amplitudes and GW energy emission.

Before describing the search, we briefly review the four scenarios listed above. If the system promptly forms a BH, the GW quasinormal-mode ringdown signal from a remnant BH in the GW170817 mass range has a dominant frequency around 6 kHz (Shibata & Taniguchi 2006; Baiotti et al. 2008). Current GW detectors are not robustly calibrated at such high frequencies. Moreover, for such a remnant BH the ringdown signal-to-noise ratio at ~ 40 Mpc is vanishingly small. We therefore focus on short and intermediate-duration GW signals from a possible NS remnant. We also do not target GW emission from a delayed NS-to-BH collapse in scenarios (ii) or (iii) as it is also not likely detectable (e.g., Baiotti et al. 2007).

A hypermassive NS is one that has mass greater than the maximum mass of a uniformly rotating star, but is prevented from collapse through support from differential rotation and thermal gradients (Baumgarte et al. 2000). Rapid cooling through neutrino emission and magnetic braking of the differential rotation causes such merger remnants to collapse $\lesssim 1$ s after formation (Shapiro 2000; Hotokezaka et al. 2013). If the star is less massive but still supramassive—i.e., its mass is larger than the maximum for a non-rotating NS—it will spin down through electromagnetic and GW emission, eventually collapsing to a BH between ~ 10 and 5×10^4 s after merger (Ravi & Lasky 2014).

Taking the posterior distribution for the progenitor masses of GW170817 (Abbott et al. 2017a), one can calculate a probability distribution for the gravitational mass of the post-merger remnant assuming conservation of baryonic mass (and neglecting mass loss to the ejecta). For a broad range of equations of state, this post-merger mass lies in the hypermassive NS regime (see Sec. 5.2 of Abbott et al. 2017c).

Moreover, observations of a kilonova-like counterpart in the optical and infrared can give insight into the remnant. For example, observations suggest low-lanthanide ejecta from the merger (Smartt et al. 2017), which may be the result of a hypermassive NS surviving $\gtrsim 100$ ms after the merger causing additional neutrino flux over that of prompt BH formation to irradiate the ejecta, increasing the electron fraction and not allowing the formation of lanthanides (Metzger & Fernández 2014; Abbott et al. 2017c,e). However, optical observations at late times also support opacity-heavy models, potentially implying a hypermassive NS lifetime < 100 ms (Smartt et al. 2017).

A hypermassive NS remnant may also partially explain the delay between the coalescence time of GW170817 and the trigger time of the short γ-ray burst (GRB) 170817A, detected 1.7 s later by the *Fermi* Gamma-ray Burst Monitor (Goldstein et al. 2017; Abbott et al. 2017c).

Simulations of merging binary NSs with hypermassive remnants show that the post-merger GW emission is dominated by the quadrupolar f-mode ($\sim$ 2—4 kHz; Xing et al. 1994; Ruffert et al. 1996; Shibata & Uryū 2000), with broad secondary and tertiary peaks in the $\sim$ 1.8—4 kHz range (Hotokezaka et al. 2013). Depending on the equation of state (EOS), the GW signal may include contributions from post-merger emission beginning around 1 kHz (Maione et al. 2017). The structure and locations of the spectral peaks is correlated with the masses and spins of the progenitors (Bernuzzi et al. 2014; Kastaun & Galeazzi 2015; Bauswein & Stergioulas 2015) and the nuclear equation of state (Read et al. 2013; Bernuzzi et al. 2015a; Rezzolla & Takami 2016), implying GW observations of a hypermassive NS potentially enable strong constraints on the equation of state (Shibata 2005; Bauswein & Janka 2012).

We also consider the scenarios (iii) and (iv) of a longer-lived post-merger remnant. Observations of X-ray afterglows following short GRBs indicate that a fraction of binary NS mergers may result in supramassive or stable NSs lasting $\gg 100\,\mathrm{s}$ (e.g., Rowlinson et al. 2013; Lü et al. 2015). GRB 170817A was sub-energetic compared to the population of cosmological short GRBs (Berger 2014; Abbott et al. 2017b; Goldstein et al. 2017), had an atypical X-ray afterglow (Evans et al. 2017; Troja et al. 2017), and had no observations hinting at a central engine remaining active following the GRB emission phase. Nevertheless, no electromagnetic observations rule out a longer-lived post-merger remnant for GW170817.

Gravitational-wave emission mechanisms in this scenario include magnetic field-induced ellipticities (Bonazzola & Gourgoulhon 1996; Palomba 2001; Cutler 2002), unstable bar modes (Lai & Shapiro 1995; Corsi & Mészáros 2009), and unstable r-modes (Lindblom et al. 1998; Andersson 1998). Estimates for the GW amplitude and detectability from such events vary across many orders of magnitude (e.g., Corsi & Mészáros 2009; Fan et al. 2013; Dall'Osso et al. 2015; Doneva et al. 2015; Lasky & Glampedakis 2016, and Sec. 4).

In summary, electromagnetic observations of this system do not provide definitive evidence for or against any of the four possible post-merger outcomes, motivating this broad search using data-analysis algorithms which are robust to uncertain waveform morphologies. We do not find any candidate post-merger GW signals associated with GW170817. This is not surprising; even considering optimistic models of GW emission from the hypermassive or supramassive NS phases, the signal-to-noise ratio for a post-merger signal from $\sim$40 Mpc in the current LIGO-Virgo network is less than $\sim$1-2 even for a matched-filter search (Takami et al. 2014; Clark et al. 2016). However, we find that our current GW amplitude sensitivity is within approximately one order of magnitude of theoretical models for post-merger GW emission, implying that, with algorithmic improvements and the LIGO-Virgo network operating at design sensitivity (Abbott et al. 2016a), as well as future detectors, such emission might become detectable.

This paper is organized as follows. In Sec. 2 we describe the detectors and data set used. In Sec. 3 we present the search methods and results for both short- and intermediate-duration GW signals. We discuss the implications and outlook for the future in Sec. 4.

2. DETECTORS AND DATA QUALITY

The LIGO (Aasi et al. 2015), Virgo (Acernese et al. 2015), and GEO600 (Dooley et al. 2016) detectors were operating at the time of GW170817. The noise amplitude spectral densities are shown in Fig. 1, where the general trend of the detectors' sensitivities at high frequencies is due to the reduced interferometer response, interrupted by non-stationary spectral features, many of which have known origins. The noise spectrum of LIGO Hanford is higher than that from Livingston in the frequency band from 100 Hz to 1 kHz; one contribution is correlated laser noise that can be subtracted off-line (Driggers et al. 2017, used e.g. for the parameter estimation in Abbott et al. 2017a). this search did not make use of such noise subtraction methods. Virgo suffered from large noise fluctuations and non-stationary spectral features at frequencies above 2.5 kHz (Acernese et al. 2015).

Due to a lack of detailed data quality studies available about GEO600, similar to those performed for LIGO and Virgo, data from that detector was not used in this analysis, although the sensitivity to a signal with time and sky location consistent with GW170817 would be roughly equal in Virgo and GEO600. We note, however, that the network signal-to-noise ratio was dominated by the two LIGO detectors.

The algorithm used to search for short-duration signals (Coherent Wave Burst, *cWB*) used only LIGO data from 1024–4096 Hz. Two algorithms were used for intermediate-duration signals: The Stochastic Transient Analysis Multi-detector Pipeline (*STAMP*) searched from 24-2000 Hz and 2000-4000 Hz in LIGO-only data, while *cWB* searches from 24-2048 Hz and used LIGO-Virgo data. These algorithms are described in Sec. 3.

We whitened and removed stationary spectral lines of instrumental origin. Other techniques were employed to minimize the impact of non-stationary spectral features (Abbott et al. 2017f). The data quality of the detectors was checked using the methods applied to previous gravitational-wave detections (Abbott et al. 2016b). A short-duration instrumental disturbance occurred in the Livingston detector 1.1 s before the coalescence time. Although this transient does not affect the performance of *cWB*, the *STAMP* analysis uses data in which the glitch is subtracted from the data (see Fig.2 in Abbott et al. 2017a).

LIGO's calibration uncertainty is 7% in amplitude and 3 degrees in phase below 2 kHz (Abbott et al. 2017a), and 8% in amplitude and 4 degrees in phase above 2 kHz (Cahillane et al. 2017). Virgo's calibration uncertainty is 10% in amplitude and 10 degrees in phase up to 5 kHz (Abbott et al. 2017a). Calibration uncertainties are not taken into account in calculations of upper limits.

3. SEARCH METHODS AND DETECTION EFFICIENCIES

In situations with great theoretical uncertainties, where no complete set of accurate GW template waveforms is available, a matched-filter search is not feasible. Instead, an efficient solution is to search for excess power in spectrograms (also called frequency-time or ft-maps) of GW detector data (Anderson et al. 2000; Klimenko & Mitselmakher 2004). Pattern recognition algorithms are used to identify the presence of GW signals in these maps (Thrane & Coughlin 2013; Sutton et al. 2010; Thrane et al. 2011; Cornish & Littenberg 2015; Klimenko et al. 2016). Here, to account for the large uncertainty in the nature of the remnant, we employ a number of algorithms, each designed to coherently combine data from multiple GW detectors, with different data-processing and clustering techniques that make them respond differently to different waveform models. These algorithms are designed to be sensitive to a wide variety of signal morphologies, and while we test their sensitivity to a number of post-merger waveform models, they are designed so as to be robust against the significant theoretical uncertainties by using generic clustering schemes. Each algorithm performs the search at a single sky position, which we take to be the direction of the host galaxy for the optical counterpart, NGC4993 (RA = 13.1634 hrs, Dec. = −23.3815°; Coulter et al. 2017; Abbott et al. 2017b). Below, we briefly describe each algorithm used in this search and present their findings.

3.1. *Short duration ($\lesssim 1$ s) signals*

We perform an analysis targeting short-duration, high-frequency GWs near the time of coalescence designed to be sensitive to unmodeled signals. This search for GW bursts is performed using the *cWB* algorithm (Klimenko et al. 2016). We search for statistically significant coherent excess power due to GW bursts in a 2 s long window which begins at 1187008882 GPS time, includes the estimated time of coalescence, and extends forward in time covering the entire delay between the merger and the GRB (1.7 s, Abbott et al. 2017c).

The *cWB* algorithm performs a maximum likelihood evaluation of coherent excess power in a multi-resolution Wilson-Daubechies-Meyer wavelet transform, which is performed on the strain from each detector (Klimenko et al. 2016). The analysis ranks candidate events by their coherent network signal-to-noise ratio. Statistical significance of candidate events is found by comparing the ranking statistic with a background distribution measured from 5.6 days of coincident data from Livingston and Hanford during the period 13–21 August. This data is "time-shifted," which means that a non-physical time lag is introduced between the detector analyzed so as to remove correlated gravitational-wave signals. This data is also "off-source," which means it is outside of the 2 s window over which gravitational waves are searched for. This analysis yields an estimate of the false-alarm probability for a given possible detection.

We search over a frequency range of 1024–4096 Hz. No significant events are found within the 2 s "on-source" window. The sensitivity of the *cWB* analysis is characterized through Monte-Carlo simulations in which waveforms from binary NS post-merger simulations are added to data from off-source periods (see Appendix A.1 for details). The simulated sources are placed at the known sky-location of the optical counterpart of GW170817 and with orbital inclination consistent with the pre-merger analysis (Abbott et al. 2017a). The waveform amplitudes are varied to determine the efficiency as a function of signal strength; see Abbott et al. (2017f) for an expanded discussion. The response of a given detector to the impinging GW is assumed to take the form

$$s(t) = F_+(\Theta,\psi)h_+(t) + F_\times(\Theta,\psi)h_\times(t), \qquad (1)$$

where F_+ and $F_\times$ are the antenna patterns for a given detector, Θ encodes the direction to the source and ψ is the polarization angle.

It is customary to express the sensitivity of a search to a given model waveform in $h_{\rm rss}^{50\%}$, which is the root-sum-squared strain amplitude of signals which are detected with 50% efficiency Abbott et al. (2017f). The detection criterion has been chosen in this specific search by setting a detection threshold on the significance of candidates which corresponds to a false-alarm probability of 10^{-4}. The quantity $h_{\rm rss}$ is defined as

$$h_{\rm rss} = \sqrt{2\int_{f_{\rm min}}^{f_{\rm max}} \left(|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2\right) \mathrm{d}f}, \qquad (2)$$

where $f_{\rm min}$ and $f_{\rm max}$ are respectively the minimum and maximum frequencies over which the search is performed. The search sensitivities are shown in Fig. 1 and Table A.1 in terms of the average frequency of each waveform, $\bar{f}$. We also provide as a point of comparison the $h_{\rm rss}$ of the same NR waveforms used in the analysis but assuming the distance of GW170817. It is worth noting that softer EOSs which lead to more compact stars exhibit a longer duration, higher frequency inspiral phase (Bauswein et al. 2013b) and a more dense remnant with relatively high frequency post-merger oscillations.

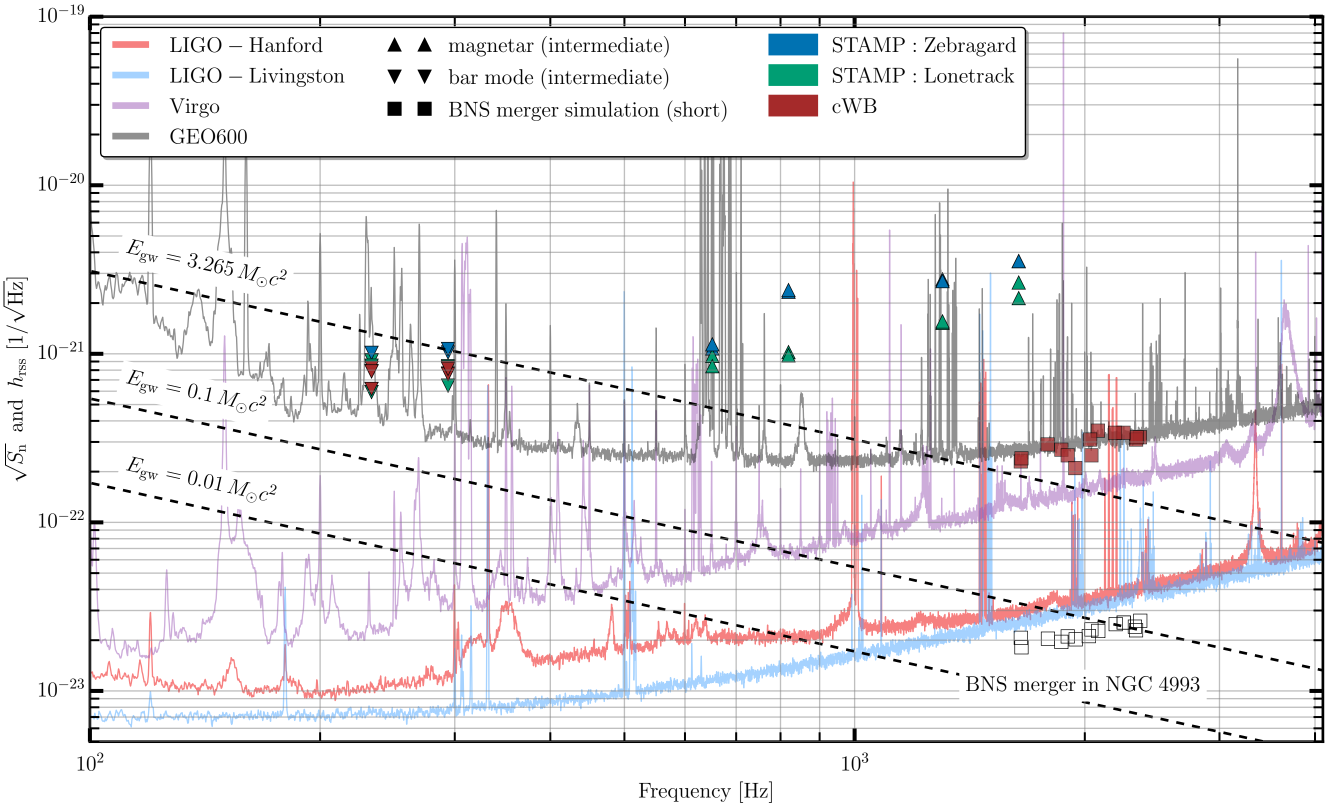

Figure 1. Noise amplitude spectral density $\sqrt{S_n}$ for the four GW detectors (solid curves), and detection efficiency root-sum-square strain amplitudes $h_{\rm rss}$ at 50% false dismissal probability for various waveforms in the short- and intermediate-duration sensitivity studies. The color code of the markers indicates the search, while the marker shapes correspond to the waveform families. The red squares correspond to the short *cWB* analysis, the red triangles to the intermediate-duration *cWB* analysis, and the green and blue triangles correspond to the intermediate-duration *STAMP* Lonetrack and Zebragard analyses respectively. The frequencies on the x-axis correspond to the average frequency of the injected waveform. The short *cWB* analysis fixes the polarization to a value consistent with the pre-merger analysis (Abbott et al. 2017a), while for intermediate durations we marginalize over polarization (see text for details). The top dashed black line indicates the maximum $h_{\rm rss}$ possible for a narrow-band GW signal with fixed energy content $E_{\rm gw}$, under the most optimistic assumption that the whole energy available after merger is radiated in GWs at a certain frequency. This energy is obtained from the pre-merger analysis (Abbott et al. 2017a) as $E_{\rm gw} = 3.265\ {\rm M}_\odot c^2$ by subtracting the lower bound of $0.025\ {\rm M}_\odot c^2$ on the radiated energy from the upper end of the 90% credible range on the total system mass. The region above this line can thus be considered an unphysical part of parameter space, and in reality we expect GW emission of only a fraction of this absolute upper bound – as an example, lines at $0.1\ {\rm M}_\odot c^2$ and $0.01\ {\rm M}_\odot c^2$ are also shown. The open squares represent the post-merger NR waveforms used in the short *cWB* analysis, but at the $h_{\rm rss}$ assuming the distance and orientation of GW170817 inferred from the pre-merger observation in (Abbott et al. 2017a). Figure produced using matplotlib (Hunter 2007).

All NR waveforms have dominant emission well-above 1 kHz, however searching from $f_{\rm min} = 1024$ Hz is a conservative choice made to avoid missing any post-merger signal content from stiff EOSs but permits pre-merger and merger-signal content from soft EOSs. In the end, the search finds no evidence for any GW signal in this band and the waveforms used to form upper limits are dominated by the postmerger phase, although they do allow for some part of the late inspiral and merger.

The strains required to produce a 50% probability of signal detection lie between $2.1 \times 10^{-22}\,{\rm Hz}^{-1/2}$ and $3.5 \times 10^{-22}\,{\rm Hz}^{-1/2}$. The GW energy radiated by an isotropically emitting source is given by Sutton (2013)

$$E_{\rm gw}^{\rm iso} = \frac{\pi c^3}{2G}\mathcal{D}^2 \int {\rm d}\Omega \int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f\ f^2 \left(|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2\right)$$
$$\approx \frac{\pi^2 c^3}{G}\mathcal{D}^2 \bar{f}^2 h_{\rm rss}^2, \qquad (3)$$

where $\mathcal{D}$ is the distance to the source. Using the $h_{\rm rss}^{50\%}$ sensitivities described above, we find that the energies to which the search is sensitive are 4.8–19.6 $\mathrm{M}_\odot c^2$, where the range corresponds to the variety of waveforms used.

We are therefore not able to constrain post-merger emission from a possible hypermassive NS associated with GW170817.

A separate analysis of the LIGO-Virgo data for unmodelled short duration bursts within a [-600,+60] second window around GRB170817A is reported in Abbott et al. (2017c) using the X-Pipeline package (Sutton et al. 2010; Was et al. 2012). This analysis searched the frequency band 20-1000 Hz. The inspiral phase of GW170817 was detected with a significance of $4.2\,\sigma$, rising to $5\,\sigma$ when the analysis is constrained to the optical counterpart location. However, no significant events were found following the merger. Limits on the amplitude of GW emission below 1000 Hz are consistent with those reported here.

3.2. *Intermediate duration ($\lesssim 500$ s) signals*

For intermediate-duration signals, we employ search algorithms adapted from the all-sky searches described in Abbott et al. (2017f). The main difference with respect to the all-sky searches is that instead of searching over many possible sky positions, we again use the known sky position of the optical counterpart. Together with the limited time range to search over, this effectively reduces the number of accidental coincident triggers. Two algorithms are employed: *STAMP* and *cWB*.

While the algorithms are sensitive to rather general waveform morphologies, we test the efficiency of signal recovery for both by a set of specific waveform models to determine $h_{\rm rss}^{50\%}$. We coherently add these simulated post-merger signals to the data of LIGO Hanford and Livingston covering the on-source period. The waveforms' polarizations are allowed to vary uniformly in ψ and $\cos\iota$, which corresponds to selecting from an isotropic distribution. The sky positions are fixed to the position of the optical transient. We describe the waveform models in the next section.

3.2.1. *Waveform Models*

Two types of physically-motivated waveform morphologies are considered, corresponding to GWs either from secular bar modes (Lai & Shapiro 1995) or caused by magnetic-field induced ellipticities of the nascent star (Cutler 2002, referred to as *magnetar* waveforms in the following). Another interesting emission mechanism are unstable r-modes (Andersson 1998; Mytidis et al. 2015); we do not use such waveforms here due to the duration of their emission, and so searches covering significantly longer timescales will be required.

The secular bar mode is a GW-driven instability (Chandrasekhar 1970; Friedman & Schutz 1975), where the growth timescale of the mode is determined by the ratio of kinetic to binding energy of the star (Lai & Shapiro 1995). The corresponding waveforms (Corsi & Mészáros 2009) and specific parameters of the model used for the waveforms are given in Appendix A.2 and Table A.2.

The magnetar waveforms assume that the merger results in a star that is rapidly spinning down, whose internal magnetic field has been wound up, generating significant stellar ellipticity (e.g., Cutler 2002; Dall'Osso et al. 2009; Ciolfi & Rezzolla 2013). The star then undergoes a spin-flip instability, causing it to become an orthogonal rotator, and hence maximal emitter of GWs. The specific waveform model is derived in Lasky et al. (2017b). The waveform is parameterized by four parameters: a braking index, stellar ellipticity, the initial GW frequency, and the spindown timescale. Details of these waveforms and their parameters are given in Appendix A.3 and Table A.3.

3.2.2. *STAMP*

STAMP employs spectrograms with 1 s × 1 Hz pixels created from the cross-correlation of data between spatially separated detectors (Thrane et al. 2011), which in this case are LIGO Hanford and LIGO Livingston. We use 500 s spectrograms covering two frequency bands: 24-2000 Hz and 2000-4000 Hz. The on-source data from the time of merger to the end of the second observing run is split into these 500 s spectrograms with 250 s overlap between them. The time-shifted off-source data is taken from August 3, 2017 until the time of the merger. These are searched with both a seed-based clustering method (Zebragard) and with a seedless pattern-recognition algorithm (Lonetrack) that integrates the pixels across tracks which are picked randomly from a large set of Bézier templates over the spectrogram (Thrane & Coughlin 2013; Thrane & Coughlin 2015).

3.2.3. *Coherent Wave Burst*

For the intermediate-duration search, the *cWB* algorithm (see Sec. 3.1 for algorithm details) searches between 24-2048 Hz using LIGO-Virgo data from the time of the merger to 1000 s later. Selection criteria for candidate gravitational wave triggers are based on the duration of the signal reconstructed by the algorithm as described in Abbott et al. (2017f). The on-source time window is taken to be the time of the merger until 1000 s later, while the off-source data is the period from 13–21 August with the data time-shifted such that no coherent signals remain.

3.2.4. *Results*

In the *STAMP* analysis, the triggers found in the on-source period are compared to the estimated background of accidental coincident triggers; there is no significant excess of coherent events during this time period in the 24-4000 Hz frequency range searched corresponding to a 10^{-2} false-alarm probability. Similarly, no GW transient candidates have been found by *cWB* above a ranking statistic value corresponding to a 10^{-4} false-alarm probability in the frequency band 24-2048 Hz.

We determine detection efficiencies for the models considered in Sec. 3.2.1. For *STAMP*, we report the equivalent energy released at which the algorithms recover 50% or more of the injected signals at a false-alarm probability of 10^{-2}, as well as the corresponding $h_{\rm rss}$. For *cWB*, we report the results at a false-alarm probability of 10^{-4}. Due to the rapid rise in background events between false alarm probabilities of 10^{-2} and 10^{-4}, the results presented here do not depend strongly on this choice. These false alarm probabilities were chosen as they correspond to a false alarm rate of approximately 1 per year. The best *STAMP* results correspond to an $h_{\rm rss}^{50\%} = 5.9 \times 10^{-22}\,{\rm Hz}^{-1/2}$ with equivalent energy of $E_{\rm GW} = 2\ {\rm M}_{\odot}c^2$ for the bar-mode signal models. The results for the *cWB* analysis are similar. For the magnetar signal models, the best *STAMP* results are $h_{\rm rss}^{50\%} = 8.4 \times 10^{-22}\,{\rm Hz}^{-1/2}$ and $E_{\rm GW} = 4\ {\rm M}_{\odot}c^2$. *cWB* did not analyze these waveforms. The energy limits are computed using Eq. 3 where isotropic GW emission is assumed and the $h_{\rm rss}^{50\%}$ values are marginalized over polarization.

4. IMPLICATIONS AND CONCLUSIONS

We report on a search for GWs from the post-merger remnant following the binary NS coalescence GW170817, using robust and generic time-frequency excess power analysis methods. Such GWs can come from a short-lived hypermassive NS lasting $\lesssim 1$ s before collapsing to a BH or from a longer-lived supramassive or stable NS. We find no evidence in our data for GWs after the merger of GW170817. If a signal exists, it is too weak to be detected with current sensitivity and analysis algorithms.

For the data set and methods employed in this paper, we find search sensitivities, in terms of GW signal amplitude, that are approximately an order of magnitude from expectations for GW emission in the literature. For example, short-lived hypermassive NSs are expected to emit a few percent of a solar mass in gravitational-wave energy (e.g., see the two lower dashed lines in Fig. 1 that represent 1% and 10% of a solar mass; Kiuchi et al. 2009; Clark et al. 2014; Bernuzzi et al. 2015b; Endrizzi et al. 2016; Dietrich et al. 2017a,b; Feo et al. 2017), while our minimum 50% efficiency is $E_{\rm GW} \lesssim 4.8\ {\rm M}_{\odot}c^2$ (see Sec. 3.1). Gravitational-wave emission from a representative sample of these numerical relativity simulations are shown as open squares in Fig. 1, which are approximately an order of magnitude in strain below the $h_{\rm rss}^{50\%}$ points for the corresponding waveforms (filled squares). For intermediate-duration signals from supramassive or stable NSs (Sec. 3.2), we find a minimum of $E_{\rm GW} \lesssim 4\ {\rm M}_{\odot}c^2$ for the millisecond magnetar model (Lasky et al. 2017b), and $E_{\rm GW} \lesssim 2\ {\rm M}_{\odot}c^2$ for the model describing secular bar modes (Corsi & Mészáros 2009).

Figure 1 shows the $h_{\rm rss}^{50\%}$ for the considered waveform models as a function of the waveform's signal-weighted frequency. Based on this, the distance of 40 Mpc for the binary NS is approximately an order of magnitude greater than the distances to which we are sensitive. This gives significant motivation to continue searching for intermediate-duration post-merger remnants in later iterations of the advanced (or future) GW detectors as well as the development of improved analysis methods.

GW170817 was detected in the second observing run of the advanced GW detectors. Further improvements towards their design sensitivity are now underway (Abbott et al. 2016a). At design sensitivity, a matched-filter search with precisely modelled post-merger waveforms could detect signals from a hypermassive NS remnant out to distances of $\sim$ 20–40 Mpc (computed as the single-detector horizon distance for a signal-to-noise threshold of 5) (Takami et al. 2014; Clark et al. 2016). Conversely, with current detector sensitivities and the more robust search methods not relying on matched filtering that are employed in this paper, a post-merger detection for GW170817 is not very likely a priori, but the theoretical uncertainties still make a search important. By using algorithms designed to be sensitive to generic signals, the searches are robust to these theoretical uncertainties and capable of detection of unmodeled signals.

This study motivates increased research and development towards improved sensitivity at high-frequencies in current instruments, planned upgrades and also third-generation interferometers. Future improvements can also be made to the search methods presented in this paper. For example, in searching for short-duration signals, the sparsity of numerical-relativity waveforms makes it challenging to perform matched-filter searches for the inspiral, merger and hypermassive phases. However, the dominant post-merger GW modes are dictated by only a few pre-merger parameters and the equation of state (e.g., Read et al. 2013; Bernuzzi et al. 2015a; Bauswein & Stergioulas 2015; Rezzolla & Takami 2016), implying more sensitive techniques can be developed that use parameters measured during the inspiral to inform priors on the physical parameters of the post-merger remnant.

A full matched-filter search is likely not computationally possible for intermediate-duration signals due to the large parameter spaces and theoretical uncertainties involved with the waveforms. However, sensitivity can be improved by targetting specific emission models (e.g., Coyne et al. 2016).

A search for longer-duration ($\gtrsim 1\,\mathrm{day}$) remnant signals is also planned, with the maximum detectable signal length limited by the 7.9 days of data available following the merger until the official end of the LIGO-Virgo second observing run. A variant of the intermediate-duration algorithms with different pixel sizes can be used to create spectrograms that cover the full duration of the analysis, making it more sensitive to longer-lived signals than the maps employed here (Thrane et al. 2015). Moreover, a variety of methods have been developed to search for persistent, nearly-monochromatic signals from mature NSs (see Prix 2009; Riles 2013; Bejger 2017, for reviews). Several of these could be modified to search for a long-lived post-merger signal, though the expected rapid decrease in frequency is likely to pose technical challenges to current algorithms.

In addition to improving the sensitivity to potential post-merger signals of GW170817, another important program is to improve our ability to detect post-merger GWs from future LIGO/Virgo discoveries of binary NS mergers. At design sensitivity, Advanced LIGO and Advanced Virgo both aim to be approximately a factor three better in broadband sensitivity than during the second observing run (Abbott et al. 2016a), and next generation detectors will improve the sensitivities significantly beyond that. This provides a number of opportunities. Clearly, increased sensitivity in the $\gtrsim$ kHz range implies improved ability to detect single post-merger signals. Moreover, increased broadband sensitivity implies higher rates of binary NS inspiral and merger detections, and hence might make possible power or coherent stacking of events to increase our sensitivity to post-merger physics (Bose et al. 2017; Yang et al. 2017).

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APPENDIX

A. WAVEFORMS

Here we provide details of the waveform models used to determine the detection efficiency of our search algorithms. For short-duration signals (Sec. 3.1) we use simulations of binary NS mergers. For intermediate durations (Sec. 3.2.1), we use two models: secular bar modes and magnetar waveforms.

A.1. *Binary neutron star waveforms*

We determine the efficacy of the short-duration *cWB* analysis (Sec. 3.1) through Monte-Carlo simulations using GW waveforms derived from simulations of binary NS systems that include a post-merger phase. Table A.1 provides a summary of the waveforms in terms of their expected $h_{\rm rss}$ for a binary NS at 40 Mpc and the $h_{\rm rss}$ required for 50% detection efficiency by *cWB* with a 10^{-4} false-alarm probability, $h_{\rm rss}^{50\%}$.

Equation of state	m_1 [$M_\odot$]	m_2 [$M_\odot$]	$\bar{f}$ [Hz]	Simulation	$h_{\rm rss}$ (expected) [$10^{-22}/\sqrt{\rm Hz}$]	$h_{\rm rss}^{50\%}$ [$10^{-22}/\sqrt{\rm Hz}$]
H4 (Glendenning & Moszkowski 1991)	1.25	1.25	1946	Takami et al. (2015)	0.21	2.1
H4 (Glendenning & Moszkowski 1991)	1.3	1.3	2083	Takami et al. (2015)	0.23	3.5
H4 (Glendenning & Moszkowski 1991)	1.35	1.35	2247	Ciolfi et al. (2017)	0.26	3.4
H4 (Glendenning & Moszkowski 1991)	1.42	1.29	2192	Ciolfi et al. (2017)	0.26	3.4
H4 (Glendenning & Moszkowski 1991)	1.54	1.26	2030	Kawamura et al. (2016)	0.22	3.1
LS220 (Lattimer & Swesty 1991)	1.20	1.50	1900	Bauswein et al. (2013a)	0.22	2.5
SHT (Shen et al. 2010)	1.40	1.40	1788	Kastaun et al. (2017)	0.21	2.9
SFHx (Steiner et al. 2013)	1.2	1.5	1650	Bauswein et al. (2013a)	0.21	2.3
SFHx (Steiner et al. 2013)	1.35	1.35	2040	Bauswein et al. (2013a)	0.24	2.5
SLy (Douchin & Haensel 2001)	1.25	1.25	2333	Takami et al. (2015)	0.23	3.2
SLy (Douchin & Haensel 2001)	1.3	1.3	2325	Takami et al. (2015)	0.25	3.1
SLy (Douchin & Haensel 2001)	1.35	1.25	2363	Takami et al. (2015)	0.27	3.2
TMA (Toki et al. 1995)	1.20	1.50	1864	Bauswein et al. (2013a)	0.19	3.2
TMA (Toki et al. 1995)	1.35	1.35	1653	Bauswein et al. (2013a)	0.20	2.4

Table 1. Sensitivity of the *cWB* pipeline to waveforms generated by binary NS simulations. Waveforms were selected to represent a variety of equations of state (first column) and progenitor mass configurations (second and third columns). The fourth column is the mean frequency for each waveform $\bar{f}$, and the fifth column is the reference for the BNS simulation. The sixth column is the root-sum-squared strain $h_{\rm rss}$ predicted by that simulation for a post-merger signal from a BNS with distance and inclination consistent with estimates from the inspiral analysis (Abbott et al. 2017a). The seventh column shows the $h_{\rm rss}$ required for 50% detection efficiency with a false-alarm probability of 10^{-4}, $h_{\rm rss}^{50\%}$.

A.2. *Secular bar mode waveforms*

Long-lived post-merger remnants may be unstable due to the secular bar-mode instability. This instability occurs when the ratio of rotational kinetic energy to gravitational binding energy $T/|W|$ is in the range $0.14 < T/|W| < 0.27$ (Lai & Shapiro 1995). For all injected waveforms used in this study we follow the treatment described in Corsi & Mészáros (2009), which we briefly summarize. We set $T/|W| = 0.2$ for the kinetic-to-gravitational potential energy ratio of the initial axisymmetric configuration (in the middle of the secular instability range). The NS spin-down is then determined by the combination of magnetic dipole and GW losses (Corsi & Mészáros 2009):

$$\frac{dE}{dt} = -\frac{B^2 R^6 \Omega_{\rm eff}^4}{6c^3} - \frac{32 G I^2 \epsilon^2 \Omega^6}{5c^5}. \tag{A1}$$

Here, B is the star's dipolar field strength at the poles, R is the mean stellar radius (i.e. the geometric mean of the principal axes of the star), Ω is the star's angular frequency, $\Omega_{\rm eff}$ is the effective angular frequency (which includes the effect of internal fluid motions), ϵ is the ellipticity, and I is the moment of inertia with respect to the rotation axis. The GW strain is then

$$h(t) = \frac{4G}{c^4}\frac{I\epsilon\Omega^2}{\mathcal{D}}, \tag{A2}$$

where Ω is found by integrating Eqn. (A1).

For all injected waveforms we assume a total NS mass of 2.6 $\mathrm{M}_\odot$, which is close to the lower bound of the estimated total mass range for GW170817 (2.73 $\mathrm{M}_\odot$; see Abbott et al. 2017a) and to the lower bound of 2.57 $\mathrm{M}_\odot$ for the total mass of other known binary NS systems (see Abbott et al. 2017a, and references therein). For a given initial $T/|W|$ value, the total radiated energy during the secular bar-mode evolution scales as M^2 (see e.g. Fig. 3 in Lai & Shapiro 1995), implying that our value of the mass can be regarded as conservative within the (optimistic) assumption that all of the total mass of the binary goes into the post-merger remnant. We use a range of magnetic field values from 10^{13} to 5×10^{14} G. Fields higher than $\sim 10^{15}$ G result in rapid spindown of the star, and hence uninteresting GW amplitudes; fields lower than $\sim 10^{13}$ G are unrealistic for such systems given the post-merger remnant dynamics that wind up strong fields. Because we do not know the ultimate fate of the bar-shaped remnant, and whether it can survive up to the ultimate Dedekind configuration (Lai & Shapiro 1995), we only evolve waveforms up to a time when the luminosity emitted in GWs is 1% of the peak value, which is sufficient to capture the bulk of the energy emitted in GWs. Table A.2 shows the specific parameters used for our waveforms, as well as $h_{\rm rss}$ at 50% efficiency computed at a fixed false alarm probability for each of the pipelines used in this search. These results are also shown in Fig. 1.

Properties					$h_{\rm rss}^{50\%}$ $[10^{-22}/\sqrt{\rm Hz}]$		
R	B	T	f_0	f_f	*cWB*	*STAMP*	
[km]	[G]	[s]	[Hz]	[Hz]		Lonetrack	Zebragard
12	10^{13}	277	449	139	8.3	8.4	10
12	10^{14}	237	449	139	8.3	9.0	9.2
12	5×10^{14}	107	449	139	7.6	6.5	7.6
14	10^{13}	509	356	111	7.9	8.1	10
14	10^{14}	396	356	111	8.1	8.3	11
14	5×10^{14}	136	356	111	6.2	5.9	7.9

Table 2. $h_{\rm rss}$ at 50% efficiency to the bar mode waveforms computed for a false-alarm probability of 10^{-2} for *STAMP* and 10^{-4} for *cWB*—see Sec. 3.2. Here, B is the star's dipolar magnetic field strength at the pole, R the mean stellar radius, T the duration of the waveform in seconds, and f_0 and f_f define the beginning and end of the frequency range where the bulk of the GW energy is emitted. Please see Sec. A.2 for further waveform details.

A.3. *Magnetar waveforms*

Gravitational waveforms from spinning-down nascent NSs with arbitrary braking index are derived in Lasky et al. (2017b). Here we assume that the rotational evolution of the star is described by the torque equation: $\dot{\Omega} \propto \Omega^n$, where n is the braking index. Integrating the torque equation enables one to derive the star's spin evolution, and hence the GW frequency

$$f(t) = f_0\left(1+\frac{t}{\tau}\right)^{1/(1-n)}, \tag{A3}$$

where f_0 is the initial GW frequency, and τ is the spindown timescale. The gravitational-wave strain is then given by Eqn. (A2), where the GW frequency is twice the star's spin frequency.

A braking index of $n = 5$ represents gravitational-wave driven spindown due to stellar ellipticity ϵ, whereas an unchanging dipolar magnetic field in vacuum induces a braking index of $n = 3$. Observations of X-ray afterglows from short GRBs allow for constraints on τ and $\Omega(t=0)$, and hence f_0 (Rowlinson et al. 2013), as well as ϵ (Lasky & Glampedakis 2016), and n (Lasky et al. 2017a). The braking index of two milllisecond magnetars have been measured, both below 3; we therefore choose $n = 2.5$ and $n = 5$ to adequately sample the space. Empirically, such stellar ellipticities are limited to $\lesssim 10^{-2}$, although theoretically such a large value is difficult to generate with internal magnetic fields as it requires a field of $\sim 10^{17}$ G. Large-scale α–Ω dynamos may generate internal fields of $\sim 10^{16}$ G (Thompson & Duncan 1993), with small-scale turbulent dynamos potentially amplifying the field to $\lesssim 5 \times 10^{16}$ G (Zrake & MacFadyen 2013), implying ellipticities as high as $\approx 2.5 \times 10^{-3}$ (Cutler 2002). In principle, the ellipticity should effect the GW frequency evolution, however in these waveform models that factor is absorbed into τ. Finally, while X-ray observations indicate $10 \lesssim \tau/\mathrm{s} \lesssim 10^5$ (Rowlinson et al. 2013), we only show waveform results here using $\tau = 100$ s as larger τ yields uninteresting GW limits.

Table A.3 shows waveform parameters used in this study and corresponding $h_{\rm rss}$ at 50% efficiency computed for a fixed false alarm probability of 10^{-2}. We do not list the duration of the waveform as all magnetar waveforms are longer than the search duration.

Properties				$h_{\rm rss}^{50\%}$ $[10^{-22}/\sqrt{\rm Hz}]$	
ϵ	n	f_0	f_{500}	*STAMP*	
		[Hz]	[Hz]	Lonetrack	Zebragard
0.01	2.5	1000	303	9.7	11
0.001	2.5	1000	303	8.4	11
0.01	5	1000	639	10	23
0.001	5	1000	639	9.8	24
0.01	2.5	2000	606	15	28
0.001	2.5	2000	606	16	27
0.01	5	2000	1278	26	35
0.001	5	2000	1278	21	35

Table 3. $h_{\rm rss}$ at 50% efficiency to the magnetar waveforms computed for a false-alarm probability of 10^{-2} for the *STAMP* pipelines used in the intermediate-duration search—see Sec. 3.2. The first four columns are respectively the stellar ellipticity ϵ, the braking index n, the initial GW frequency f_0, and the GW frequency after 500 s f_{500}, which is the duration of the analyses. Please see Sec. A.3 for further waveform details.

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