Supernova and Prompt Gravitational-wave Precursors to LIGO Gravitational-wave Sources and Short GRBs

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Abstract

Binary black holes (BBHs) and binary neutron stars (BNSs) mergers have been recently detected through their gravitational-wave (GW) emission. A post-merger electromagnetic counterpart for the first BNS merger has been detected from seconds up to weeks after the merger. While such post-merger electromagnetic counterparts had been anticipated theoretically, far fewer electromagnetic precursors to GW sources have been proposed, and none have been observed. Here we show that a fraction of a few $10^{-3}$ (for a standard model) GW sources and short gamma-ray bursts (GRBs) observed by the Laser Interferometer Gravitational-wave Observatory (LIGO) could have been preceded by supernova (SN) explosions from years up to decades before the mergers. The GW sources are produced following the preceding binary evolution, the supernovae involved in the final formation of the GW source progenitors, and the natal kicks that likely accompany them. Together, these determine the orbits of surviving binaries, and hence the delay-time between the birth of the compact binary and its final merger through GW emission. We use data from binary evolution population-synthesis models to show that the delay-time distribution has a non-negligible tail of ultra-short delay-times between 1 and 100 years, thereby giving rise to potentially observable supernovae precursors to GW sources. Moreover, future LISA/DECIGO GW space-detectors will enable the detection of GW inspirals in the pre-merger stage weeks to decades before the final merger. These sources could therefore produce a unique type of promptly appearing LISA/DECIGO GW sources accompanied by coincident supernovae. The archival (and/or direct) detection of precursor (coincident) SNe with GW and/or short GRBs will provide unprecedented characterizations of the merging binaries, and their prior evolution through supernovae and natal kicks, otherwise inaccessible through other means.

Key words: binaries: general – gamma-ray burst: general – gravitational waves

1. Introduction

The recent detection of gravitational-wave (GW; Abbott et al. 2016a, 2016b, 2017b, 2017c, 2017d) mergers of double-compact-object (DCO) binaries (binary black holes (BBHs), BNSs (binary neutron stars), neutron star–black hole (NS–BH) binaries yet to be detected) has opened up a new era of GW astronomy. The joint detection of GWs and post-merger electromagnetic (EM) counterparts (GW170817/GRB170817A) allows for the unprecedented characterization of compact objects, their GW inspiral, and their final merger. Moreover, the identification of a short gamma-ray burst (GRB) EM counterpart to the NS–NS merger in GW170817/GRB170817A provided the first direct confirmation for the origin of short GRBs from BNS mergers (Goodman 1986; Paczynski 1986; Eichler et al. 1989).

Extensive studies of the possible progenitors of GW sources gave rise to a wide range of models and possible expectations for the rates and properties of GW mergers. Post-merger EM counterparts of such events had been anticipated theoretically and/or recently observed to occur from seconds up to weeks after the merger (Abbott et al. 2017a, and references therein). However, EM precursors to GW sources, not yet observed, had been little explored, and are the focus of the current study. Such precursors could provide unique information on progenitor systems otherwise inaccessible through other proposed/observed EM counterparts.

Models for DCO mergers explored the expected delay-time between the formation of the second compact object in the DCO through a supernova (SN; and/or direct collapse) and the final detectable merger (e.g., Belczynski et al. 2006a, 2008; Dominik et al. 2012). The delay-time distribution (DTD) can provide valuable information and constraints regarding the expected environment of the GW sources (star-forming/old). Therefore, DTD studies focused on understanding of the overall distribution and correspondence of young/old populations (e.g., Belczynski et al. 2006b, 2007, 2008; Dominik et al. 2012; de Mink & Belczynski 2015), but did not consider the detailed tail distribution. This, however, could be critical in the context of EM precursors (Michaely et al. 2016, hereafter Paper I). Here we focus on the tail distribution of the ultra-short delay-times (USDs), ranging from a year up to a century, and show that they constitute a small but non-negligible fraction of GW events. Such ultra-short delay sources have important implications, as they give rise to a unique type of potentially observable SN-precursor counterparts to GW sources. The SNe arise from the final formation of the second compact object accompanying the GW source, and precede its final merger by a timescale of only 1–100 years. Note that although DTDs are extensively discussed in the literature, the potential of ultra-short delays in giving rise to preceding EM counterparts is explored here systematically and in detail for the first time, to the best of our knowledge. Moreover, USDs can result in a unique type of GW source, promptly appearing in the middle of the detectable frequency band of next-generation LISA/DECIGO GW detectors (Danzmann & Rüdiger 2003; Kawamura et al. 2006), and accompanied by concurrent SN counterparts, as we discuss here.

The outline of this Letter is as follows. We begin in Section 2 by describing the data and models for the GW binary progenitor that we obtained from publicly available population
synthesis studies. Then in Section 3 we calculate the detailed GW inspiral evolution for each of the binary progenitors with USDs from the available models, and obtain their GW strain and frequencies by following their orbital properties as they evolve to the final merger. We present our main results regarding the expected fractions and properties of USD events in Section 4, and then discuss and summarize them in Section 5.

2. Population Synthesis Models and Data

We use the data from the population synthesis study by Dominik et al. (2012), openly available in the Synthetic Universe online database (http://www.syntheticuniverse.org), from which we extracted the orbits of DCOs upon their initial formation. Dominik et al. (2012) studied a wide range of models for the formation and evolution of DCOs in the field and their merger rates (i.e., no dynamical/tidal capture processes are taken into account). They used the StarTrack population synthesis code (Belczynski et al. 2002, 2008) and explored the differences in the expected properties and their dependence on the model assumptions and parameters. They focused on some of the main uncertainties involved in binary stellar evolution, and considered several models/parameters for the common envelope (CE) phase: the maximal masses expected for NSs; the wind mass-loss rate prior to the SN; and the natal kick for the NS–BH. They created two subsets of 16 models named A and B, which differ in their treatment of the core-envelope transition problem (see details in Belczynski et al. 2007). For each model they also considered two possible metallicities, $Z = Z_\odot$ and $Z = 0.1 Z_\odot$. Altogether they explored $2 \times 2 \times 16 = 64$ models. For each model they followed the evolution of $10^6$ binaries and extracted all the compact-binaries formed through the evolution, including (1) BH–BH, (2) BH–NS, and (3) NS–NS binaries.

The difference between subset models A and B due to the core-envelope transition is an important one. Submodel A ignores the core-envelope problem and just takes the energy balance into account, while submodel B assumes the CE phase with Hertzsprung gap donors leads to a merger and hence reduces the fraction of post-CE surviving binaries.

The parameter $\lambda$ describes the binding energy of the envelope, and is defined as

$$E_{\text{bind}} = -\frac{GM_{\text{donor}}M_{\text{donor,env}}}{\lambda R} \quad (1)$$

where $R$ is the radius of the donor star. In Dominik et al. (2012) the authors used seven different values of $\lambda$: four with fixed values (V1–4), one calculated as described in their Section 2.3.2, termed $\lambda_{\text{Nanjing}}$ following Xu & Li (2010) and Loveridge et al. (2011; in their “standard” model); in models V14 and V15 they vary $\lambda_{\text{Nanjing}}$ by a factor of 5 and 1/5, respectively. The merger rate also depends on the final NS mass; in V5 a maximal mass of $M_{\text{NS,max}} = 3 M_\odot$ is considered, while in V6 it is assumed that $M_{\text{NS,max}} = 2 M_\odot$. Next the natal kick issue is addressed in model V7; where the authors consider low-velocity natal kicks, drawn from a Maxwellian distribution with velocity dispersion of $\sigma = 132.5 \, \text{km s}^{-1}$ for both NS and BH. In V8 they consider a high-velocity natal kick for the BH, while in model V9 the BHs are not kicked at all. In V10 they use a delayed supernova engine (as compared with the rapid engine used in the standard model). Different wind schemes are explored in models V11–V13. In V11 the mass-loss rates are reduced by 50% (compared with their standard model); in V12 they assume a fully conservative mass transfer, while V13 is a fully non-conservative mass transfer. A brief summary of all models considered can be found in Table 1; detailed explanations of each model can be found in the original paper by Dominik et al. (2012).

3. Evolution of GW Inspirals

Massive binary systems can potentially lead to the formation of DCO binaries. A fraction of these systems will merge within a Hubble time via GW emission. For a DCO system to form it needs to survive the binary stellar evolution, including the CE phases, and the two SNe that produce the compact object components (notwithstanding direct collapse, which may produce a silent/fainter transient event when a BH is formed$^1$). Here we focus on the properties of the formed DCO binaries and their final inspiral through GW emission, searching for sufficiently rapid inspirals leading to mergers on $<100$ years timescales. For this purpose, we follow the GW inspiral of each of the DCO binaries extracted from the models, and derive their properties and evolution in the strain-frequency domain of current/future GW detectors.

If a DCO binary forms following the complex earlier stellar evolution, it then evolves only through GW emission. The equations that govern the dynamics in GW-emitting systems

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$^1$ Generally, the more massive BHs are more likely to be produced following a direct collapse, and therefore the expected rates for these could be a few times lower. However, current understanding suggests that there is no single-parameter mapping between progenitor mass and the final remnant (Woosley et al. 1986; Heger et al. 2003; Belczynski et al. 2004; Ertl et al. 2016).
are given by Peters (1964) as
\[
\frac{da}{dt} = -\frac{64}{5} \frac{G^3 m_1 m_2 (m_1 + m_2)}{c^5 a^3 (1 - e^2)^{3/2}} \left( 1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right) \tag{2}
\]
\[
\frac{de}{dt} = -\frac{304}{15} \frac{G^2 m_1 m_2 (m_1 + m_2)}{c^5 a^4 (1 - e^2)^{3/2}} \left( 1 + \frac{121}{304} e^2 \right) \tag{3}
\]
where \(c\) is the speed of light, \(G\) is Newton’s constant, \(m_1, m_2\) are the DCO masses, and \(a, e\) are the binary semimajor axis and eccentricity, respectively. The averaged rate at which a system dissipates its orbital energy is given by Peters & Mathews (1963) as
\[
\left\langle \frac{dE}{dt} \right\rangle = -\frac{32}{5} \frac{G^2 m_1^2 m_2^2 (m_1 + m_2)}{c^5 a^5 (1 - e^2)^{7/2}} g(n, e) \tag{4}
\]
where \(\langle \cdot \rangle\) indicates orbital averaging. For circular orbits the entire energy is radiated through the second \(n = 2\) harmonic of the binary orbital frequency \(f_{\text{bin}} = (2\pi)^{-1} (G(m_1 + m_2)/a^3)^{1/2}\). For eccentric orbits the energy radiated in the \(n\)th harmonic is given by Peters & Mathews (1963) as
\[
E_n = \left\langle \frac{dE_n}{dt} \right\rangle = -\frac{32}{5} \frac{G^2 m_1^2 m_2^2 (m_1 + m_2)}{c^5 a^5 (1 - e^2)^{7/2}} g(n, e) \tag{5}
\]
where \(g(n, e)\) is the enhancement factor given by
\[
g(n, e) = \frac{n^2}{32} \left\{ J_{n-2}(ne) - 2 e J_{n-1}(ne) + \frac{2}{n} J_n(ne) + 2 e J_{n+1}(ne) - J_{n+2}(ne) \right\}^2 + (1 - e^2) [J_{n-2}(ne) - 2 e J_{n-1}(ne) + J_{n+2}(ne)]^2 + \frac{4}{3n^2} L_n^2(n) \tag{6}
\]
where \(J_n(x)\) is the \(n\)th Bessel function. The characteristic strain and frequency of the GW signal can be derived from these equations, given a specific distance. For the sky-orbit average Barack & Cutler (2004) presented the characteristic strain for the \(n\)th harmonic:
\[
h_{c,n} = \frac{1}{\pi R} \sqrt{\frac{2 E_n}{n \times f}} \tag{7}
\]
where \(R\) is the luminosity distance. Given Equation (7) we can calculate the GW signal for a given binary and determine whether it is detectable by a specific GW detector. For example, the green line-dashed curve in Figure 1 shows the evolution of a BH–NS binary system from DCO birth (the leftmost point; lowest frequency; highest separation), until the merger (rightmost point; highest frequency; closest separation).

Considering the assumed distance to the GW source and the system parameters (see the figure), one can determine the detailed evolution of the binary and the characteristic strain and frequency of the GW signal during the evolution. The three solid black lines correspond to the sensitivity curves of LIGO, DECIGO, and LIGO. The black circles, down-pointing triangles, up-pointing triangles, squares, and diamonds represent 1 s, 1 hr, 1 day, 1 year, and 10 years before merger, respectively. Gray dots correspond to the initial position of all the ultra-short systems that merge within 100 years. All values are calculated assuming a luminosity distance of \(R = 50\) Mpc.

4. Results

In order to better explain our detailed results, we first consider a few specific cases that represent well the various type of ultra-short delay binaries. In Figure 1 we plot five examples for the evolution of the characteristic strain of several types of DCO systems. All examples are calculated for a luminosity distance of \(R = 50\) Mpc and originate from the subset-A models with \(Z = 0.1\) Z_{⊙}. A “typical” binary system is
depicted by a thin gray line. This BH–BH binary begins outside the LISA-band, and inspirals for \(\sim 200\) Myr as it enters and crosses the LISA and DECIGO bands until it merges inside the LIGO band. The other examples depict several examples from the sample of USDs binaries. Two NS–NS binaries are shown; the first, depicted by the dotted blue curve, forms following a significant natal kick, and begins its evolution in a highly eccentric orbit (see detailed parameters in the figure caption). This system is not detectable immediately at birth (i.e., it is not a promptly appearing GW source; see the next section), but begins its evolution outside the detection range. It then evolves, circularizes, and enters into the DECIGO sensitivity curve on a short, decades-long timescale (a similar evolution for a BH–BH binary is depicted by the red dashed line). We note that for an initially eccentric binary, several harmonics carry the GW energy; the signal can even be dominated by the higher harmonics for a fraction of the time (see Figure 1). The second NS–NS binary, depicted by the solid blue curve, forms with a moderate eccentricity and promptly appears inside the DECIGO detection band. Given its expected strain, it would be observable by DECIGO even up to \(R \approx 650\) Mpc. The dashed green curve corresponds to a BH–NS binary promptly appearing at birth in the LISA-band, which only 10 years later already merges inside the LIGO band, likely producing a short GRB. The gray dots show the initial position of all USD binaries that merge within 100 years in all the models that we considered (1688 binaries in total). Figure 2 similarly shows all the ultra-short delay systems (within 100 years; marked in blue), compared with all the other, much longer delay-time systems, merging within 1 Gyr (gray dots; 368485 systems). With this better understanding of the type of USD systems and their comparison to other DCO systems, we are now ready to discuss the specific fractions and distributions for the various models.

4.1. Delay-time Distributions of GW-sources and Short GRBs

We calculated the evolutionary path for each of the merged binaries, as well as for each one of the DCO cases in the data set of Dominik et al. (2012). The detailed evolutionary sequel provides us with the overall delay-time for each binary, as well as the relevant GW signal, frequency, and strain (normalized by the assumed distance to the source).

Figure 3 shows the fraction of systems that merge within some short-time \(t_{\text{thresh}}\) = 5 years, 50 years, and 100 years (from bottom to top; green, red, and blue markers, respectively) out of the total number of systems that merge in less than 14 Gyr. BH–BH, BH–NS, and NS–NS binaries are represented by squares, diamonds, and circles, respectively. The majority of the models in Figure 3 produce merging NS–NS/BH–NS binaries within 100 years with comparable fractions (\(5 \times 10^{-4}\) up to \(10^{-2}\)) for solar-metallicity models, and comparable but higher fractions for the low-metallicity models. Models V1 (solar metallicity V2) and model V15 are the exception. V1 does not produce any ultra-short delay systems due to the low-\(\lambda\) parameter, leading to the merger of potential progenitors already during the CE phase. By contrast, model V15 (high-\(\lambda\)) produces a large number of surviving progenitors, with 0.1 of NS–NS systems merging in <100 years.

Interesting results also emerge from model V8, where no natal kick is given to the BH. We therefore expect to find a large fraction of BH–BH binaries surviving the CE phase and merging on short timescales. The same analysis holds for submodel B, (see the right column of Figure 3), showing only slightly lower fractions due to the smaller number of surviving binaries (due in this case to the core-envelope transition). Note that in cases where no kicks are imparted, the initial eccentricity of the binaries is lower, and they are more likely to be detectable in both LISA and DECIGO. Such systems, however, have relatively large initial pericenter separation, and without the kicks never attain the initial sufficiently small separations that give rise to the shortest delay-times. Indeed, although the fraction of systems merging in 100 years timescale is large, none of these systems merge in <10 years. We refer the reader to Paper I for a discussion and analytic treatment of the natal kicks role in the formation of USD GW sources.

For the standard model with sub-solar metallicity we expect a fraction of \(\sim 3 \times 10^{-3}\) of all BNS mergers to have a SN precursor within 100 years. Given a detection rate of \(R = 1540 +3200_{-1220}\) Gpc\(^{-3}\) years\(^{-1}\) (Abbott et al. 2017a) and assuming
that we can detect a merger within 200 Mpc, the detection rate of precursor SN to BNS is in the range $6 \times 10^{-3}$–$0.12 \text{ yr}^{-1}$.

### 4.2. Prompt GW Sources in LISA/DECIGO

Future GW space-detectors such as the planned LISA and DECIGO missions will be sensitive to the GW signal arising from the early pre-merger inspiral stage of DCO binaries, from weeks up to decades before the merger (Sesana 2016; Chen & Amaro-Seoane 2017). USD mergers could therefore appear promptly in the middle of the LISA/DECIGO frequency band, coincident with an SN detection (e.g., dashed-dotted green and solid blue lines in Figure 1). Such a prompt appearance differs from the typical sources that form at low frequencies outside of the observable range and then evolve slowly to higher frequencies entering the LISA/DECIGO band; e.g., see the BH–BH solid gray line in Figure 1. Such sources will therefore not be accompanied by a precursor/coincident SN. The prompt GW sources discussed here therefore constitute a unique type of source with a unique signature. Note that at least for close-by (50 Mpc) sources (see Figure 2), many binaries with longer delay-times ($>100$ years) could also promptly appear and have a coincident SN, but will not reach the LIGO band during a human lifetime.

### 5. Discussion and Summary

In this Letter we study the evolution and properties of DCO binaries that inspiral and merge on USD (years to decades) typically following an SN explosion. The short delay-times between the SN and the final merger enable the potential detection of the SN as an observable EM precursor to LIGO GW sources and/or short GRBs (the latter arising only from NS–NS/NS–BH mergers). Because these binaries typically originate from post-CE binaries with significantly interacting binary progenitors, the SN precursor counterparts that we identify are likely to be Type-Ib/c SNe originating from massive stars that lost their outer envelopes during the binary evolution. Given the short delay-time, such events will only be expected in star-forming regions/host galaxies. Moreover, given the short time that would have elapsed since the second SN, the potentially (natal-)kicked binary will not have had sufficient time to further propagate from its birthplace in the galaxy, and such systems would be found at relatively small offsets from their star-forming region birthplaces. The short timescales would also suggest that the final merger will occur inside an SN remnant, which might also affect potential radio/X-ray signals from the interaction of ejected material/jet from BNS mergers, producing short GRBs and the SN remnant debris.

The identification of a GW merger event in LIGO with a preceding SN within years to decades would also provide a smoking-gun signature for the binary-evolution origin of the DCO, rather than a dynamically formed GW source. The latter sources are not expected to have such precursors, as they form long after the formation of both DCO components. Depending on the level of localization of the GW sources, precursor SNe could be paired with specific GW sources at a high probability given the localization of the GW source/short GRB to a specific galaxy, but might prove more challenging for poorly localized GW events, given the background noise of SNe in a large ensemble of potential host galaxies. The sky localization of a LIGO/Virgo GW detection (without an EM counterpart) is $\sim 10 \text{ deg}^2$; for DECIGO it is $\sim 0.1 \text{ deg}^2$ (Singer et al. 2016). Hence, taking a Type-Ib/c rate of $\sim 1000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Singer et al. 2016)
and a source at $\sim 500^{+100}_{-100}$ Mpc, we expect a rate of $\sim 10^{-2}$ yr$^{-1}$ coincident Type-Ib/c SNe in the LIGO/Virgo localization volume, and $\sim 10^{-3}$ yr$^{-1}$ for DECIGO. We note that with an EM counterpart the localization is reduced to a galaxy scale, where the expected rate for a Milky-Way-like galaxy is $\sim 10^{-3}$ yr$^{-1}$.

The fractions of expected sources with SN precursors are sufficiently high in the majority of the models, such that a few events might be expected among the hundreds to thousands of GW sources expected to be detected in the coming years, especially with the upgraded LIGO-VIRGO-KAGRA consortium combined with an all-sky SN survey. Such identification would provide us with a direct link between an SN that formed the secondary DCO component and the properties of the DCO binary, and will potentially also inform us about the type of binary that could form an USD GW source. A statistical sample of such events would further constrain the evolutionary models of DCO binary progenitors.

Finally, we propose the existence of a novel type of promptly appearing GW sources observable by next-generation GW space-detectors. The induced final stages of binary evolution, and/or the natal kick given to the second-formed compact object, can produce a USD GW source, which initial configuration would position in the midst of the LISA/DECIGO detection range already upon their formation, rather than the typical case of GW sources entering the detection range from lower frequencies. Moreover, such events could be coincidentally observed with the SN. The coincidence would allow a much better pairing of the SN to the GW event, even with a less-than-optimal localization of the GW source, and such pairing would serve as an important and unique source of information about such events and their origins.

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