

On the formation of neutron stars via accretion-induced collapse in binaries

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ABSTRACT

We investigate evolutionary pathways leading to neutron star (NS) formation through the collapse of oxygen–neon white dwarf (ONe WD) stars in interacting binaries. We consider (1) non-dynamical mass transfer where an ONe WD approaches the Chandrasekhar mass leading to accretion-induced collapse (AIC) and (2) dynamical time-scale merger-induced collapse (MIC) between an ONe WD and another WD. We present rates, delay times, and progenitor properties for two different treatments of common envelope evolution. We show that AIC NSs are formed via many different channels and the most dominant channel depends on the adopted common envelope physics. Most AIC and MIC NSs are born shortly after star formation, though some have delay times > 10 Gyr. The shortest delay time (25–50 Myr) AIC NSs have stripped-envelope, compact, helium-burning star donors, though many prompt AIC NSs form via wind accretion from an asymptotic giant branch star. The longest delay time AIC NSs, which may be observed as young millisecond pulsars among globular clusters, have a red giant or main-sequence donor at the time of NS formation and will eventually evolve into NS + helium WD binaries. We discuss AIC and MIC binaries as potential gravitational wave sources for Laser Interferometer Space Antenna (LISA). NSs created via AIC undergo a low-mass X-ray binary phase, offering an electromagnetic counterpart for those shortest orbital period sources that LISA could identify. The formation of NSs from interacting WDs in binaries is likely to be a key mechanism for the production of LIGO/Virgo gravitational wave sources (NS–NS and BH–NS mergers) in globular clusters.

Key words: gravitational waves – binaries: close – stars: evolution – stars: neutron – white dwarfs – x-rays: binaries.

1 INTRODUCTION

It is mostly accepted that accretion from a stellar companion on to a massive carbon–oxygen (CO) white dwarf (WD) either produces a Type Ia supernova (SN), or quiescently burns into an oxygen–neon-rich (ONe)¹ WD, as it approaches the Chandrasekhar mass

limit ($\sim 1.4 M_{\odot}$). The exact burning criterion that determines what actually occurs in nature is still a subject of debate (Nomoto & Kondo 1991; Yoon & Langer 2005; Schwab, Quataert & Kasen 2016). It is also not completely clear what happens to even heavier, ONe or hybrid CONe WDs (Siegel 2006; Karakas 2014) as they approach the Chandrasekhar mass, though the general consensus is that an ONe WD will collapse to form a neutron star (NS) (Miyaji et al. 1980). If the ONe WD is able to achieve central densities of the order of $\sim 10^{10} \text{ g cm}^{-3}$, either through stable accretion from a binary companion (Hurley et al. 2010) or through mergers (Saio & Nomoto 1985), electron-capture reactions on Ne-20 and Mg-24 likely cause the WD to collapse before a thermonuclear

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¹We note that a non-negligible fraction of other carbon-burning products, such as Mg-24, are likely to be present in the WD. However, we adopt ‘ONe WD’ to refer to all ONe-rich WDs that also include Mg.

runaway is able to run its full course (see also Jones et al. 2016). Thus, in addition to NSs born from traditional iron core-collapse SNe from massive stars, and electron-capture SNe (ECSNe) born from degenerate ONe cores with zero-age main sequence (ZAMS; for single stars) masses $\sim 7\text{--}10 M_{\odot}$, we also expect a population of NSs born from the accretion-induced collapse (AIC) of heavy WD stars in interacting binaries.

NSs created via single stellar evolution are born shortly after the onset of star formation with a narrow range of delay times, due to the intrinsically massive nature of their progenitors. Having said that, there is plenty of evidence showing that core-collapse SNe from massive stars may commonly occur in binary star systems (Smith 2014), and binary interactions indeed have the effect of pushing the delay time distribution toward larger delay times (Zapartas et al. 2017). Binary evolution effects widen the mass range where ONe WDs are expected to form and enable NSs to be born with a wider range of natal kick velocities (Podsiadlowski et al. 2004) and as we will show, delay times.

The relative fraction of NSs formed via WD accretion in binaries relative to core-collapse NSs formed from massive stars will likely be higher in environments harbouring high stellar densities (Ivanova et al. 2008). It is generally assumed that millisecond pulsars (MSPs) are old NSs that were formed in core-collapse events of massive stars and then subsequently spun up via mass accretion (but see also van den Heuvel & Bonsema 1984). This ‘recycling’ scenario was first suggested by Backus, Taylor & Damashek (1982). However, this is in tension with the evidence that at least some pulsars found among old stellar populations (e.g. globular clusters) exhibit properties consistent with those of young NSs. This anomaly can easily be explained by NSs formed via AIC (Lyne, Manchester & D’Amico 1996; Boyles et al. 2011; Tauris et al. 2013). Hurley et al. (2010) investigated formation rates of AIC NSs using population synthesis methods (see also Ivanova & Taam 2004; Ferrario & Wickramasinghe 2007; Belczynski et al. 2010b; Liu et al. 2018) and found that AIC systems provide a complementary, if not more important, formation pathway to MSPs than recycling. For a discussion on various formation channels leading to MSPs, we refer the reader to Smedley et al. (2017).

Given that current and future deep synoptic sky surveys such as SkyMapper (Wolf et al. 2018), the Zwicky Transient Facility (Bellm et al. 2019), and the Large Synoptic Survey Telescope (LSST Science Collaboration 2017) will continue to unveil an unprecedented number of stellar transients with unknown origin, it is of course worthwhile to predict the most promising observable signatures of different transient candidates; accreting, ultramassive WDs being the main focus of this work. We distinguish between NSs formed by stable Roche lobe overflow (RLOF) accretion (AIC) and those formed in mergers (merger-induced collapse, or MIC) for the sake of predictions: the former may potentially be observed during their last mass transfer phase shortly before the WD collapses to an NS or after the NS is born during a low-mass X-ray binary (LMXB) phase, while the latter progenitors will be difficult to detect without future, sensitive, space-based gravitational wave observatories such as Laser Interferometer Space Antenna (LISA, see Section 3.3).²

From the standpoint of nucleosynthesis, demarcating the boundaries separating the conditions for WD collapse versus thermonuclear explosion is critical for delineating the progenitor parameter

space between NSs formed in binaries and Type Ia SNe (Saio & Nomoto 1985; Maoz, Mannucci & Nelemans 2014). This has important consequences for chemical evolution and by extension, Galactic archaeology. Calculations by Kromer et al. (2015) have shown that light curves and spectra of near-Chandrasekhar mass hybrid CONe WDs that undergo a so-called failed deflagration could explain faint Type Iax SNe, such as 2008ha, but do not appear to be able to explain ‘normal’ Type Ia SNe. Marquardt et al. (2015) calculated light curves and spectra of thermonuclear SNe arising from exploding ONe WDs, and though there are some similarities with 1991T-like (very luminous) events, there is no clear match to a particular transient subclass, substantiating the widely held belief that ONe WDs do not explode (see also Wu, Wang & Lie 2019). However, a recent multidimensional hydrodynamical study by Jones et al. (2016) found that collapse of an ONe WD to an NS can be avoided in cases where the assumed semiconvective mixing during the electron-capture phase preceding the deflagration is inefficient (resulting in lower central densities at ignition). In these cases, the oxygen deflagration results in a weak explosion that leaves behind a bound remnant containing some iron-group material (see also Vennes et al. 2017; Jones et al. 2018). The higher central density cases, reflecting very efficient semiconvective mixing, on the other hand showed clear signs of collapse of the WD to an NS.

An AIC to an NS is indeed expected to be a faint event, certainly compared to ‘normal’ thermonuclear SNe, and also compared to iron core-collapse SNe. ECSN explosions are predicted to have much lower explosion energies ($\lesssim 10^{50}$ erg, Dessart et al. 2006; Metzger, Piro & Quataert 2009) compared to other core-collapse SNe whose typical explosion energies are $(0.6\text{--}1.2) \times 10^{51}$ erg. In the case of an AIC to an NS, ejecta masses have previously been estimated to be in the range of a few $\times 10^{-3}$ to $\sim 0.05 M_{\odot}$ (Dessart et al. 2006; Darbha et al. 2010; Fryer et al. 1999). Even though double NS mergers remain the favoured site for explaining most *r*-process material (Côté et al. 2018a), if the conditions for AIC are similar to those of simulated ECSNe, it is reasonable to suppose that AIC events could provide one of the elusive formation sites for the weak *r*-process (Wanajo, Janka & Müller 2011; Cescutti & Chiappini 2014). By providing physical properties of the binary systems that we predict will produce NSs via induced-collapse (both stably accreting and mergers) from binary evolution population synthesis, we hope to motivate further, detailed studies of interacting ultramassive WDs. In addition, recent works have proposed that AIC and/or MIC NSs could potentially give rise to other exciting phenomena as well, including fast radio bursts (Moriya 2016), magnetars (Piro & Kollmeier 2016), and gamma-ray bursts (Lyutikov & Toonen 2017), and they could make an important contribution to gravitational wave astronomy [see Section 3.3, and Lipunov (2017)]. More specifically, NSs that are formed by induced-collapse channels can contribute toward producing double NS mergers in globular clusters (Belczynski et al. 2018).

We use the STARTRACK binary evolution population synthesis code (Belczynski et al. 2008; Belczynski, Kalogera & Bulik 2002; Ruiter et al. 2014) to determine the birth rates, ages (delay times), and evolutionary pathways of binary star systems that lead to the birth of an NS. We assume two cases for NS formation: (1) an ONe-rich WD in a binary that accretes matter from its companion until it approaches the Chandrasekhar mass limit and collapses into an NS (AIC) and (2) a dynamical merger of two WDs, where at least one of them is already ONe-rich, leading to the birth of an NS via mass accretion (up to Chandrasekhar) on to the more massive WD (MIC, Ivanova et al. 2008). It remains to be established whether the scenarios proposed above lead in reality to an NS rather than e.g. a

²Though for MIC progenitors, the merger itself may indeed involve an electromagnetic counterpart, especially if a large amount of mass (on the order of $0.2 M_{\odot}$) is ejected during the merger (e.g. Brooks et al. 2017).

black hole (BH). For example, a binary system may experience two AIC events: first a WD collapsing to an NS, then the NS collapsing to a BH (Belczynski & Taam 2004). In general, the outcome clearly depends on the final mass of the object produced via collapse and on the maximum mass that can be attained by an NS (Timmer, Woosley & Weaver 1996). However, this limiting mass is difficult to ascertain because the initial to final mass relationship for NSs is not well constrained by observations (see Margalit & Metzger 2017, and references therein). In this paper, we make the assumption that all such systems will yield NSs, even in the case where the combined mass at time of WD merger exceeds $2.5 M_{\odot}$ which is the canonical upper NS mass limit assumed in *STARTRACK* (see Section 3). Since the common envelope (CE) phase is the most important source of uncertainty in the formation of WDs in binaries (De Marco 2009), we employ two different parametrizations for CE evolution to bracket the (unknown) uncertainties in the formation of these systems. The two CE treatments are described in Section 2.

2 MODEL

We use the *STARTRACK* rapid binary evolution population synthesis code to evolve two populations of binary stars consisting of 12.8×10^6 systems each, starting from the ZAMS. The code has undergone many updates in recent years. Updates especially relevant for the study of intermediate-mass stars include the addition of a new treatment for CE evolution (Xu & Li 2010b; Dominik et al. 2012), an updated prescription for the treatment of helium accretion on to WDs (Ruiter et al. 2014; Kwiatkowski 2015), and the fact that we now allow a WD to gain mass from a stellar companion that is experiencing wind mass loss at a high rate (Belczynski et al. 2016).

Initial orbital parameters. Initial ZAMS star masses are drawn from a three-component power-law initial mass function (IMF) based on Kroupa, Tout & Gilmore (1993) with $\alpha_1 = -1.3$, $\alpha_2 = -2.2$, and $\alpha_3 = -2.35$. The initially more massive star (M_1) is chosen in the mass range $0.8\text{--}100 M_{\odot}$ while the companion's (M_2) mass range is $0.5\text{--}100 M_{\odot}$. M_1 is drawn directly from the probability distribution function given by our chosen IMF, and M_2 is calculated by picking a value for the mass ratio $q = 0\text{--}1$, e.g. $M_2 = qM_1$, where q is chosen with a flat probability distribution. We assume circular orbits from the ZAMS rather than the thermal distribution usually adopted in our previous work. This guarantees a higher degree of reproducibility (for comparison purposes) with other population synthesis code data (the majority of binary population synthesis codes assume circular orbits during mass transfer phases, and a circular orbit sometimes must be imposed by hand for a fraction of binaries that would not have circularized naturally due to tidal interactions). We note that assuming $e = 0$ for every ZAMS binary may not be the most realistic assumption particularly for binaries with large orbital periods (>2 d, see Moe & Di Stefano 2017). For interacting binaries, where separations are already rather small, we do not expect a major impact on our final results. However, we note an overall smaller birth rate for MIC systems when compared to simulations where non-zero initial eccentricity is adopted (see Section 4.1).

For the orbital separations on the ZAMS, we adopt the canonical initial distribution (flat in the logarithm), up to $10^5 R_{\odot}$, with the lower limit set by:

$$a_{\min} = f_{\min} \frac{(R_{1,0} + R_{2,0})}{(1.0 - e_0)} \quad (1)$$

where $f_{\min} = 2$ is a stellar radius multiplication factor defining the minimum orbital size, $R_{1,0}$ and $R_{2,0}$ are the ZAMS radii of stars

M_1 and M_2 , respectively, and the initial eccentricity e_0 is set equal to zero in this paper. Both populations are evolved with near-solar ($Z = 0.02$) metallicity. While we do not conduct a parameter study of metallicity here, we note that event rates are generally higher for lower metallicity, for reasons related to wind-mass-loss rates, described in Côté et al. (2018b). We discuss the potential impact that initial helium fraction could have in our study in broad terms in Section 4.2.

Common envelope evolution. A CE is encountered when mass from the donor star is transferred to the accretor on a time-scale that is far too short for the accretor to adjust thermally to the incoming material. As a consequence, this material heats up and swells, filling the Roche lobe. Further mass loss from the donor will form an envelope engulfing both stars. The difference between the two population models is due to the difference in how the binding energy parameter λ (see equation 2) is estimated during CE evolution. Though significant progress has been made in quantifying the CE phase numerically over recent years (De Marco et al. 2011; Ricker & Taam 2012; Ivanova et al. 2013; Ohlmann et al. 2016), we are far from a comprehensive understanding of this critical phase of binary star evolution.

In population synthesis studies, the CE phase cannot be explicitly calculated but must be somehow parametrized. A common way to do this is to equate the binding energy of the envelope of the mass-losing star with the orbital energy of the binary system. The envelope will then be expelled from the system at the expense of the binary's orbital energy (Webbink 1984), which causes the orbital size to decrease, often drastically. It is reasonable to assume that the binary's post-CE separation is determined by the energy reservoirs in the system that are available, however, we do not know how orbital energy can be transferred to the removal of the envelope; in fact it may not even be a correct assumption (Nelemans 2005). Further, it is not clear which energy reservoirs are even at our disposal (internal energy, ionization energy, and enthalpy, see e.g. Ivanova & Chaichenets 2011). For this reason, the CE efficiency parameter α_{ce} (Livio & Soker 1988) and the binding energy parameter λ (de Kool 1990) were introduced. These parameters contain our limited knowledge on the physics of CE evolution.

Setting the change in orbital energy equal to the binding energy gives:

$$\alpha_{\text{CE}} \left(\frac{GM_{\text{com}}M_{\text{core}}}{a_{\text{fin}}} - \frac{GM_{\text{com}}M_{\text{core+env}}}{a_{\text{init}}} \right) = \frac{GM_{\text{core+env}}M_{\text{env}}}{\lambda R_{\text{core+env}}}, \quad (2)$$

where M_{com} is the mass of the companion star (which is not losing its envelope), M_{core} is the mass of the core of the envelope-losing star, $M_{\text{core+env}}$ and $R_{\text{core+env}}$ are the total stellar mass and radius of the envelope-losing star, and a_{fin} and a_{init} represent the final and initial orbital separations (post- and pre-CE), respectively.

For Model 1, we adopt the CE formalism employing energy balance (Webbink 1984) that historically was the favoured prescription used in binary population synthesis codes with $\alpha_{\text{ce}}\lambda = 1$. We refer to Model 1 as the 'classical CE' model. Higher values of $\alpha_{\text{ce}}\lambda$ correspond to larger envelope ejection efficiency which, in turn, leads to wider post-CE orbital separations. However, more plausibly, the mass-losing stars' state of evolution will play a role in determining the binding energy of the envelope, and thus will directly affect the value of the binding energy term. For this reason, we adopt a second CE model that takes the evolutionary stage of the donor into account, while keeping the efficiency parameter, α_{ce} , constant ($= 1$).

It has been clear for many years that adopting a constant value for the binding energy parameter during the CE phase is not the

most physical, and therefore probably not the best, assumption (Dewi & Tauris 2000). It is known however that the parameter λ is very sensitive to the structure of the mass-losing star, namely the definition of the core-envelope boundary (Dominik et al. 2012), which is not trivial to prescribe. None the less, we can approximate a value for λ based on the evolutionary stage of the donor, envelope mass, and radius as calculated from detailed stellar evolution models (Xu & Li 2010b) in an attempt to ensure that these quantities have an influence on the efficiency with which the envelope is ejected (and thus the post-CE separation). For Model 2, we still use the same energy balance formula (equation 2) but use a more sophisticated approach to estimate the donor binding energy parameter λ . We denote this as the ‘new CE’ model. Within the context of the energy balance formalism, numerical simulations of CE ejection in recent years have revealed that seemingly unphysically high values for ejection efficiency are required to expel the envelope during the CE phase. One possible mechanism that was proposed to help the ejection process is stationary mass outflows (Ivanova & Chaichenets 2011). Including such a mechanism, effectively accounting for the enthalpy of the envelope, in the standard energy balance formalism for CE ejection introduces a correction factor by increasing the binding energy term (effectively reducing the binding energy). Such a result is desirable since it enables better agreement with binary population synthesis models and their predicted numbers of BH LMXBs.

To estimate the binding energy, we use the revised fits of Dominik et al. (2012) based on the data from Xu & Li (2010a,b). In STARTRACK we have introduced (Wiktorowicz, Belczynski & Maccarone 2014) the possibility to take into account enthalpy arguments presented by Ivanova & Chaichenets (2011). These models allow for a physical estimate of donor star binding energy that depends on stellar mass, as well as its evolutionary stage and chemical composition (e.g. larger values of λ for more evolved donors). In the new CE model, the binding energy parameter value ultimately depends on the evolutionary state of the donor when the CE phase begins. Using table 1 of Ivanova & Chaichenets (2011) for intermediate-mass stars as a guide, we increase the binding energy parameter (estimated from our new mass and evolutionary stage-dependent λ approach) by a factor of 2, thereby decreasing the binding energy by a factor of 2.

Stable RLOF on WDs. For binaries in RLOF (the AIC progenitors), we assume that mass accretion proceeds with the same prescription for ONe WDs as it does for CO WDs (see Ruiter, Belczynski & Fryer 2009; Ruiter et al. 2014, for hydrogen- and helium-rich accretions, respectively), being dependent on the rate at which mass is transferred toward the accretor, and on the mass of the accreting WD. Thus, our adopted prescription is slightly different from the one adopted in Hurley et al. (2010), which assumes no mass dependence on the WD accretor for the accretion rate. We also assume that mass transfer of CO (or ONe) on a CO or ONe WD is fully conservative (see Belczynski et al. 2008, for further details on how mass transfer phases are calculated). We assume that any CO WD that approaches the Chandrasekhar mass will produce an SN Ia, regardless of the accretion rate. Thus only ONe WDs are considered to undergo AIC in our simulations (but see Section 3.2).

Stellar winds. STARTRACK employs various prescriptions from the literature for the treatment of stellar winds. For low-mass stars, we adopt the wind prescription of Hurley, Tout & Pols (2002, see Belczynski et al. 2010a, for further details), while for Wolf–Rayet helium stars, the wind prescription is based on Hamann & Koesterke (1998), with a metallicity dependence adopted from Vink & de Koter (2005). For low- and intermediate-mass evolved stars, it is

reasonable to assume that some material lost by the donor may be accreted by a close companion. In fact, such assumptions are likely necessary for re-producing observed properties of carbon-enhanced metal-poor stars (Abate et al. 2013). We assume that a WD can accrete mass from the wind of a nearby companion asymptotic giant branch (AGB) star donor assuming a Bondi–Hoyle accretion configuration, though this assumption may be conservative, since some simulations have shown wind accretion efficiency from evolved donor stars could be notably higher (Mohamed & Podsiadlowski 2007). For our AIC progenitors with AGB donors, which will lose $\sim$ a few $M_{\odot}$ on the AGB, the time-averaged accretion rate is $\sim 10^{-8} M_{\odot}$ per year. This AGB wind accretion model is capable of producing AIC NSs from ONe WDs that are born with masses already very close to the Chandrasekhar mass limit.

Neutron star formation. There are different ways in which an NS can form from an intermediate-mass star. ECSNe form NSs via the collapse of a degenerate ONe core (Nomoto 1987; Jones et al. 2013; Woosley & Heger 2015). The ZAMS mass of an ECSN progenitor is not extremely well constrained since it will depend on stellar wind mass loss suffered by the star as well as binary interactions, if applicable. However, the helium core mass at the base of the AGB is thought to be $\lesssim 2.5 M_{\odot}$ (see Chruslinska et al. 2018, and references therein). ECSNe have been predicted to comprise roughly 4 per cent of all core-collapse SNe (Wanajo et al. 2011).

The main difference between the progenitors of ECSNe and AIC is that the ONe core of an ECSN precursor is still surrounded by He- and H-burning shells, which allows the ONe core to grow in mass, collapse, and subsequently suffer a deflagration (Hillebrandt, Nomoto & Wolff 1984). This different configuration may affect the resulting nucleosynthesis during and possibly also after the formation of the NS. In this work, we do not discuss general ECSN formation channels but focus on the sub-population of NSs formed through evolutionary channels that involve the collapse of a WD star in an interacting binary. Below, we summarize the conditions for AIC and MIC.

Today, one of the most promising progenitor scenarios for the formation of Type Ia SNe is the merger of two CO-rich WDs (Nomoto & Iben 1985; Pakmor et al. 2010, 2012; Ruiter et al. 2013; Tanikawa et al. 2015), with some support for CO WDs merging with He-rich WDs (Dan et al. 2015; Fenn, Plewa & Gawryszczak 2016; Crocker et al. 2017; Brown et al. 2017). It is still under investigation whether the WD merger proceeds via ‘accretion up to Chandrasekhar’, in which case the explosion mechanism would likely be similar to the classic single degenerate scenario (e.g. Röpke et al. 2007; Seitenzahl et al. 2013), or occur via prompt detonation such as the ‘helium-ignited violent merger model’ of Pakmor et al. (2013, see also Shen & Moore 2014). Analogous to CO WDs, in our binary evolution population synthesis simulations concerning ONe WDs we do not differentiate between the two types of merger scenarios, and we include all heavy WD mergers as potential MIC candidates. For the MIC scenario, we assume that an NS is formed any time an ONe-rich WD merges with another WD regardless of its composition or total mass (which always exceeds $1.5 M_{\odot}$, see Section 3). In our models, ONe WDs only merge with CO WDs or ONe WDs. This is because for other, less-massive WD types (e.g. He-rich), the mass ratio is far from unity and thus when the less-massive WD fills its Roche lobe mass transfer is dynamically stable, and a merger is avoided in our models (cf. Côté et al. 2018b, section 6.2). For instance, most of the observed AMCVn systems, which are short-period binaries where a He-rich star (likely a WD) transfers mass to its more massive WD companion (Solheim 2010; Provencal et al. 1997), exhibit dynamically stable

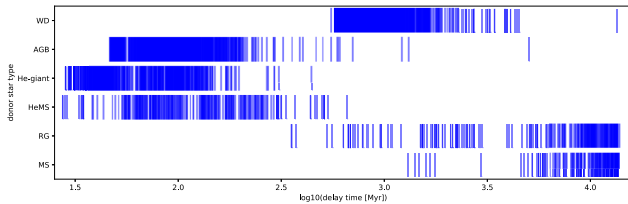


Figure 1. Distribution of delay time versus donor star type at time of AIC for the classical CE prescription. Each line represents one binary system. Regions of solid colour are regions of high number density in the delay time – donor-type parameter space.

mass transfer, although it has been suggested that some of these binaries, whose mass ratios are closer to unity, may undergo explosive events such as SNe Ia or SN .Ia (Bildsten et al. 2007; Perets et al. 2010).

In the AIC scenario, we assume that when any ONeWD approaches the Chandrasekhar mass limit via stable accretion, an NS is formed. Although STARTRACK can follow the evolution of each system after the formation of the NS, this is beyond the scope of this work to examine the future evolution of the entire AIC population. However, we comment briefly on the future evolution of some AIC binaries in Sections 3 and 4. We do not include AIC formed via CO WDs in our simulations, though in Section 3 we estimate the number of AIC NSs we expect could potentially arise from this channel.

3 RESULTS

3.1 Progenitors and delay times

We find that AIC and MIC systems occur with a full range of delay times. Though both AIC and MIC NSs can be born up to a Hubble time (or beyond) after star formation, most are formed within 200 Myr after starburst.

3.1.1 AIC donor types

In Figs 1 and 2, we show donor star companion type versus delay time for the binary systems that undergo AIC for our classical and new CE models, respectively. The numbers are raw data and thus not calibrated to fit the characteristics (e.g. star formation rate over time) of the Milky Way (MW). It is immediately obvious that AIC progenitors involving MS, giant-like or WD donors have the longest delay times; these are systems that plausibly represent the population of ‘young’ NSs found among globular clusters. Their delay times start from greater than a few hundred Myr and extend to beyond a Hubble time. AIC progenitors with the most prompt delay times arise from binaries where the donor star has lost its hydrogen envelope but is still helium-burning (He giant or He MS). AIC progenitors that may arise via wind accretion from a late AGB star have relatively short delay times, too (most within a few hundred Myr). The shortest delay time NS in our models is found in the new CE model, at a delay time of 28 Myr with a stripped-envelope, compact helium-burning star donor (sometimes referred to as a main-sequence helium star). The initial masses of the stars were 12.82 and 7.97 $M_{\odot}$ with an initial separation of 31 $R_{\odot}$. We describe some specific evolutionary channels in Appendix A.

Though the overall AIC birthrates are similar for both CE models (see Section 3.2), there are some notable differences between them, such as in the classical CE model, AIC progenitors with AGB donors

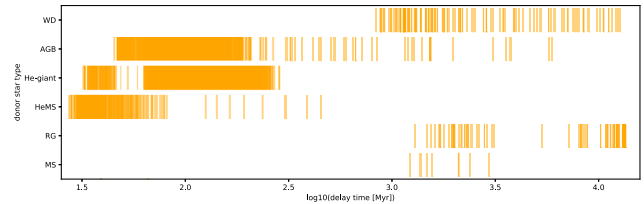


Figure 2. Like Fig. 1: distributions of delay time versus donor star type at time of AIC for the new CE prescription.

dominate strongly over all other donor types (though comparable with H-envelope-stripped He-burning star and WD donors), while H-envelope-stripped He-burning stars strongly outnumber other donor types in the new CE model. The driving factor behind why different channels may be more prominent in one CE model but not in the other stems back to the fact that, in general, the new CE model gives rise to wider post-CE orbits. This is the reason why e.g. there is a factor of 6 more WD-AIC systems in the classical CE model versus the new CE model.

3.1.2 MIC white dwarf masses

In Figs 3 and 4, we show number density distributions of the total WD mass at time of MIC merger as a function of delay time for the classical and new CE models, respectively. Some massive binaries merge at late delay times for both CE models. These systems go through one CE event, rather than two CE events; the latter are common for the events with delay times < 1 Gyr. Note that in some systems, it is the same star that undergoes a CE twice [first losing its hydrogen envelope, then later its helium envelope, see Ruiter et al. (2013)]. Just like AIC NSs, MIC NSs can form at very long delay times.

We overplot with a dashed line the maximum NS mass that is normally allowed in STARTRACK (2.5 $M_{\odot}$ is the typically chosen parameter value). There are not many events above this threshold in either model, though we assume that in the event that an NS is born, any mass above this threshold would have to leave the system to avoid collapsing to a BH. We also show with a dotted-dashed line the upper mass limit expected for an NS from the recent study of Margalit & Metzger (2017), who find a maximum NS mass of only 2.17 $M_{\odot}$. We find ~50 per cent and ~20 per cent of our MIC systems lie above 2.17 $M_{\odot}$ in our classical and new CE models, respectively. However, in the new CE (classical) model, about 90 per cent (60 per cent) of these compact mergers form through an evolutionary channel that involves an unstable phase of mass transfer while the mass-losing star is only a slightly evolved giant. We assume that such a configuration would result in a CE phase, though other works have pointed out that binaries in this configuration may avoid a CE phase under these conditions (see Section 4).

In Figs 5 and 6, we show number density distributions of primary versus secondary WD mass (initially more massive versus initially less massive star). For comparison, a similar figure in Lyutikov & Toonen (2017, see their fig. 5) has a sharp discontinuity along the primary mass range ~1–1.1 $M_{\odot}$, though we note that they only consider CO + ONe WD pairs in their models (no double ONe WD pairs). It is not surprising that the different population synthesis codes reproduce similar results in terms of predicted pre-merger WD masses (see also Toonen et al. 2014). The different regions of ‘clumps’ is a result of different evolutionary channels (see Section 3.3).

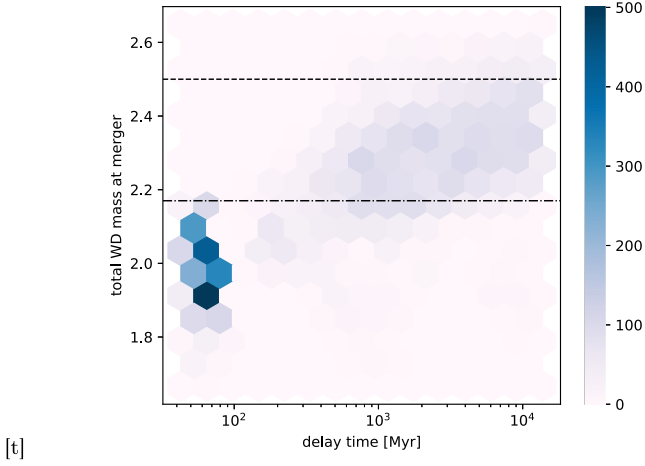


Figure 3. Number density distributions of delay time versus total WD mass at time of MIC for the classical CE prescription (darker colour means more systems in that time-mass bin). Horizontal lines correspond to the assumed NS upper mass limit, above which the compact object is likely to become a BH in STARTRACK (dashed line) and Margalit & Metzger (2017, dotted–dashed line, see the text).

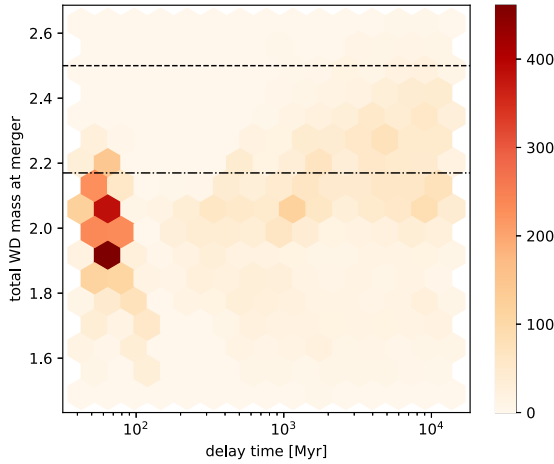


Figure 4. Number density distributions of delay time versus total WD mass at time of MIC for the new CE prescription. Horizontal lines correspond to the assumed NS upper mass limit, above which the compact object is likely to become a BH in STARTRACK (dashed line) and Margalit & Metzger (2017, dotted–dashed line, see the text).

3.2 Birth rates

We predict birthrates of AIC and MIC systems for our binary star populations. Our rates are calibrated per unit mass formed in stars and are calculated by assuming a binary star fraction of 70 per cent. There is no strong change in Galactic birth rate with adopted CE model. We find a current combined (AIC + MIC) Galactic birth rate that is roughly an order of magnitude below the observationally inferred Galactic SN Ia rate: $\sim 1.3 \times 10^{-4} (\pm 0.4 \times 10^{-4})$ and $\sim 1.7 \times 10^{-4} (\pm 0.4 \times 10^{-4})$ AIC per year for the classical and new CE models, respectively. We find a similar though slightly higher rate for MIC: $\sim 2.3 \times 10^{-4} (\pm 0.4 \times 10^{-4})$ and $\sim 2.3 \times 10^{-4} (\pm 0.4 \times 10^{-4})$, respectively. For our Galactic birth rates, we assumed a constant star formation rate (see below).

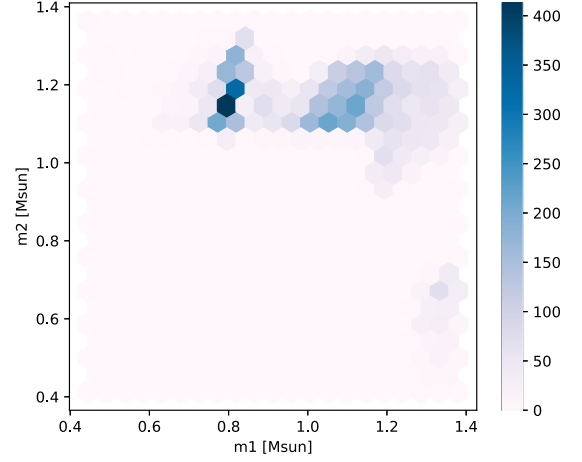


Figure 5. Number density distributions of WD masses at time of merger for the initially more massive star (x-axis) and initially less massive star (y-axis) for the classical CE prescription (darker colours mean more systems in that mass–mass bin).

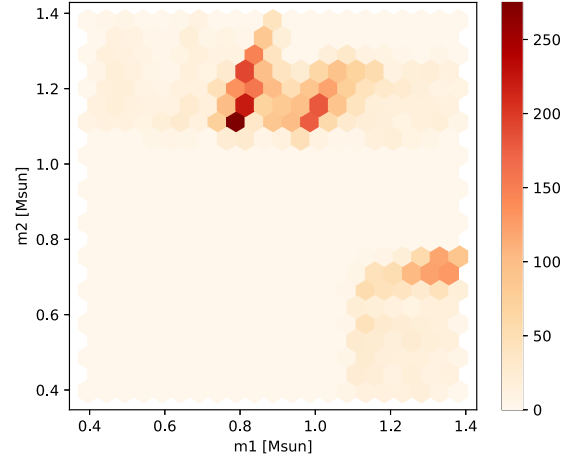


Figure 6. Number density distributions for WD masses at time of merger for the initially more massive star (x-axis) and initially less massive star (y-axis) for the new CE prescription.

The explanation for the lower number of ONe+ONe mergers in the new CE model is as follows. The main difference between the progenitors of ONe+ONe mergers and those of ONe+CO mergers is that ONe+ONe mergers typically undergo only one CE phase, whereas CO+ONe mergers normally undergo two CE phases. For the ONe + ONe MIC progenitors, the single CE event happens when the donor star is only slightly evolved (a red giant or in the Hertzsprung gap), and thus it would have a higher binding energy parameter λ in the new CE model (by a factor of a few) compared to the classical CE model ($\lambda = 1$; see Section 2). As a consequence, the binding energy of the donor star in the new CE model is lower so the separation of the stars after CE is somewhat wider, and the binary never achieves contact again within a Hubble time. We comment on the likeliness of binary system survival during a CE phase when the giant-like donor does not have a strongly distinct core-envelope structure in Section 4.

In Table 1, we show relative formation rates (over a Hubble time) from our raw data for NSs formed through different AIC and MIC channels. We also present current birth rates estimated

Table 1. Relative total number of AIC events (different donor channels) and MIC events from STARTRACK that occur per simulation of 12.8 million ZAMS binaries that are allowed to evolve for a maximum of 13.7 Gyr. First two columns of values represent relative raw simulation AIC or MIC events over a Hubble time. The birth rate columns are expected current Galactic birth rates of AIC or MIC events. In the last column, we list general characteristics typical of the progenitor (and in some cases post-NS evolution of the) system.

Channel	Class. CE tot	New CE tot	Class. CE rate (yr ⁻¹)	New CE rate (yr ⁻¹)	General characteristic
AIC+main sequence	145	9	$\leq 1e-5$	$\leq 1e-6$	Few $R_{\odot} \lesssim a \lesssim 10 R_{\odot}$, donors $1-2 M_{\odot}$ at AIC
AIC+sub/red giant	231	81	$\leq 1e-5$	$\leq 1e-6$	Donors $\sim 1 M_{\odot}$ at AIC, short post-AIC RLOF phase, end up as NS+He-rich WD binary on $\sim 10^1-10^2 R_{\odot}$ orbit
AIC+stripped He-burning	844	3178	$3e-5$	$1.8e-4$	$1 R_{\odot} \lesssim a \lesssim 10 R_{\odot}$, $\dot{M} \sim \text{few } 10^{-6} \text{ yr}^{-1}$; post AIC LMXB phase with $\dot{M} \sim \text{few } 10^{-8} \text{ yr}^{-1}$, later end up as NS+COWD binary on small orbit
AIC+AGB wind	1112	1173	$3e-5$	$3e-5$	Thermally pulsating AGB, wide orbit
AIC+WD	809	140	$3e-5$	$\leq 1e-6$	$\dot{M} \sim \text{few } 10^{-6} \text{ yr}^{-1}$, usually He WD donor, then LMXB with $\dot{M} \sim \text{few } 10^{-8} \text{ yr}^{-1}$
MIC CO+ONe	7192	6017	$2.2e-4$	$2.2e-4$	Many channels; 1–3 RLOF phases and 1 or 2 CE phases
MIC ONe+ONe	913	368	$3e-5$	$4e-5$	Usual channel involves 2 RLOF phases (H then He donor), 1 CE event (HG star), 1 RLOF event (He donor)

for the MW Galaxy, assuming a constant star formation rate over 10 Gyr and a total stellar Galactic mass of $6.4 \times 10^{10} M_{\odot}$. The most dominant channel in our simulations is the hydrogen-stripped helium-burning star donor channel: we find similar results to Wang (2018) for their CE model [our rates bracket, but are on the lower end of, the rates for two adopted α_{CE} models of Wang (2018)]. However, our giant-like and main-sequence donor channels are a factor of a few to an order of magnitude below those found by Wang (2018).

For birth rates, we have assumed the same simple star formation history of $6 M_{\odot} \text{ yr}^{-1}$ that was adopted in Lyutikov & Toonen (2017). Our MIC birth rates are within the range found by Lyutikov & Toonen (2017): $\sim 2-5 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$, depending on their adopted CE formalism. Our predicted Galactic AIC rates are somewhat higher than those forecast by Yungelson & Livio (1998) that amount to 8×10^{-7} to 8×10^{-5} events per year. When comparing our AIC birth rates to the binary MSPs formed via AIC of Hurley et al. (2010),³ our numbers are within agreement (see their table 1) if we make the assumption that all AICs make MSPs. This is plausibly justified considering that conservation of angular momentum would naturally cause the NS to spin at millisecond periods and the conservation of magnetic flux would produce an NS with magnetic fields in the range 10^8-10^9 G, typical of MSPs, without having to invoke accretion induced field decay (Ferrario & Wickramasinghe 2007; Smedley et al. 2015). On the other hand, Tauris et al. (2013) pointed out that the formation of NSs may be inevitably accompanied by the generation of strong magnetic fields,

and thus these AIC NSs would need to undergo further accretion to reach the observed weaker fields.

As mentioned previously, it is theoretically possible that a CO WD can undergo quiescent burning and evolve into an ONe WD under the right burning conditions. It is therefore worthwhile to estimate how many accreting CO WDs in our STARTRACK models may contribute toward the AIC progenitor population. In STARTRACK, the canonical assumption is that if a CO WD approaches the Chandrasekhar mass limit it will produce a Type Ia SN, regardless of the accretion rate, but we have estimated the number of AIC NSs that could arise from the CO WD channel in a post-processing step. Following Wang, Podsiadlowski & Han (2017), we check our simulations for CO WDs that undergo accretion where the initial accretion rate exceeds $2.05 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ and the CO WD mass is close to Chandrasekhar ($> 1.35 M_{\odot}$) at the end of the accretion phase. We find that the CO WD AIC channel can contribute up to 20 percent of what we find from our combined ONe AIC WD channels. This fraction is in rough agreement with the results of Wang (2018).

We note that our predicted Galactic rates of AIC events are in agreement with upper limit estimates set by Solar system abundances of neutron-rich isotopes, which is $\sim 10^{-4}$ AIC per year (Fryer et al. 1999; Dessart et al. 2006; Metzger et al. 2009). Though it remains to be confirmed which isotopes are synthesized in AIC events, if AIC NSs are indeed a formation site for a subset of neutron-rich isotopes (including *r*-process), local abundance patterns could potentially provide a useful lower limit on Galactic AIC formation rates (De Silva et al. 2015). If we consider the fact that AIC NSs may leave behind a hot remnant of ionized gas that is potentially visible for up to 100 000 yr, analogous to what has been predicted for the Chandrasekhar mass (i.e. single degenerate)

³Hurley et al. (2010) also assumed a constant star formation history but at a higher rate of $8.6 M_{\odot} \text{ yr}^{-1}$, and used different assumptions for CE evolution.

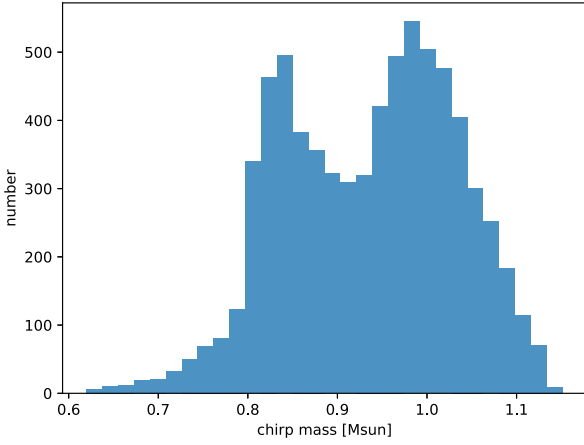


Figure 7. Chirp mass distribution of heavy WD pairs leading to MIC events for the classical CE model.

scenario of Type Ia SNe (Woods et al. 2017), we estimate that on the order of ~ 10 of these post-AIC remnants could currently exist in the Galaxy today.

3.3 MIC and AIC progenitors as gravitational wave sources

It has been shown that the gravitational wave signature of Galactic double WD binaries with orbital periods of less than about 5 h will be detectable with future space-based gravitational wave observatories, like LISA (Nelemans, Yungelson & Portegies Zwart 2004; Ruiter et al. 2010; Cornish & Robson 2017). The most massive, very nearby binaries with the shortest orbital periods will have the best chance to be individually resolved as gravitational wave sources (Nelemans 2013). A quantity that is a function of the component masses, the chirp mass $M_{\text{chirp}} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$, can be directly measured from gravitational waves (e.g. if f_{GW} and $\dot{f}_{\text{GW}}$ are measurable). The (dimensionless) strain amplitude, h , is proportional to $M_{\text{chirp}}^{5/3}$ via

$$h = 2(4\pi)^{1/3} \frac{G^{5/3}}{c^4} f_{\text{GW}}^{2/3} M_{\text{chirp}}^{5/3} \frac{1}{r} \quad (3)$$

where the gravitational wave frequency of a binary with a circular orbit is $f_{\text{GW}} = 2/(P_{\text{orb}})$, where P_{orb} is the orbital period, and r is the distance to the binary from the detector. h is a measure of the fractional change in separation that occurs (e.g. between detector nodes, or spacecrafts) when a gravitational wave passes through the detector. Naturally, as the binary approaches merger time, its orbital period decreases drastically and thus f_{GW} increases (sweeping, or ‘chirping’ across the frequency band). Note that the orbital frequency evolution can also be negative, such as in the case of some mass-transferring binaries (Kremer et al. 2017).

In Figs 7 and 8, we show the distribution of MIC progenitor chirp masses for the classical and new CE approaches, respectively. The distribution of chirp masses is bimodal in the classical CE model, but it has only one peak in the new CE model. The reason for the different distribution shapes is attributed to the different formation channels that dominate depending on the CE model. The fact that different formation channels are more (less) prominent than others depending on the CE model results in a different ranges of chirp mass being more (less) populated than others.

In the classical CE model, two main peaks are visible in Fig. 7: the highest peak is $\sim 0.83 M_{\odot}$, and another broader peak centred

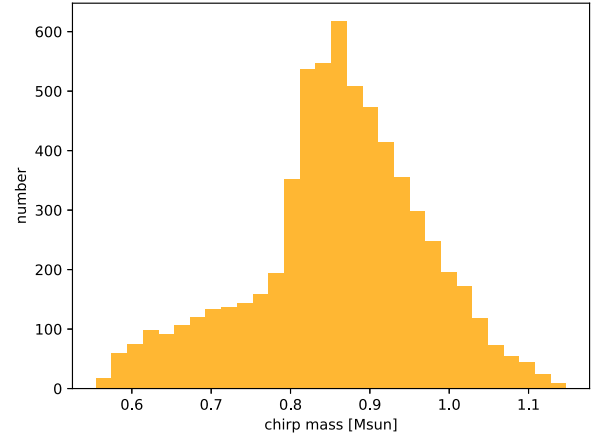


Figure 8. Chirp mass distribution of heavy WD pairs leading to MIC events for the new CE model.

$\sim 1 M_{\odot}$ (see Example 2 in Appendix A). The first peak corresponds to progenitors with delay times less than 300 Myr arising from different formation channels. The systems with chirp masses below $\sim 0.79 M_{\odot}$ are almost exclusively arising from progenitors with delay times greater than 300 Myr that undergo two CE events: first when the primary is an AGB star, then later when the secondary is a red giant. These MIC systems populate the lower right quadrant of Fig. 5.

In the new CE model for MIC progenitors, the peak in Fig. 8 $\sim 0.87 M_{\odot}$ is dominated by two formation channels: one short (~ 70 Myr) delay time channel (see Appendix Example 3) and one long (~ 11 Gyr) delay time channel. The systems that populate the parameter space with lower chirp masses consist mostly of short delay time MIC binaries that undergo one stable mass transfer event (primary star loses mass to secondary), and two CE events (primary and then secondary star losing envelope, or secondary star loses its envelope: first hydrogen envelope then later the helium envelope). These MIC systems populate the lower right quadrant of Fig. 6. The binaries populating the higher chirp mass part of the distribution are almost exclusively from one formation channel with very short (~ 40 Myr) delay times and the following mass transfer phases: (1) stable mass transfer from a Hertzsprung Gap star (primary) toward main-sequence star, (2) stable mass transfer from a naked helium-giant (primary) to a main-sequence star, (3) a CE phase between a (secondary) star in the Hertzsprung Gap and a CO WD, and (4) stable mass transfer between an H-envelope-stripped helium-burning giant (secondary) and the CO WD. This final phase is the higher mass analogue of what occurs during the evolution of some Type Ia SN progenitors (stage VIII) uncovered in Ruiter et al. (2013).

If binaries in fact do survive a CE phase that involves a Hertzsprung Gap star (see Section 4), then our predictions indicate they will have some of the highest chirp masses among the double WD binary population. Given the relatively low birth rate of NSs created by MIC, we do not expect to ‘see’ an MIC event with LISA (would have to be lucky!), but our calculations indicate that a number of MIC progenitor systems will be visible in the LISA band (see below). Since MIC progenitors comprise a sub-population of the total double WD population, we can be more optimistic at the prospect of detecting the lower mass (and more numerous) double WD systems, e.g. CO+CO WD binaries, many of which are likely Type Ia SN progenitors. We look forward to the time when gravitational wave measurements of close binary stars can finally

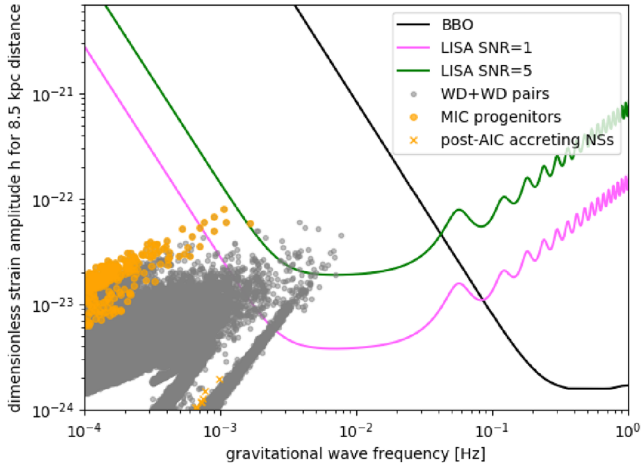


Figure 9. Gravitational wave strain amplitude of Galactic double WDs (grey), including MIC progenitors (orange dots) as well as post-AIC binaries that have since started a phase of RLOF (e.g. LMXBs; orange crosses) for our new CE model. We have plotted the strain amplitude for a distance of 8.5 kpc to give a general idea of the parameter space (in terms of h and f_{gw}) that we expect our binaries to populate at the current epoch. Note that the true gravitational wave signal will depend on several factors, distance being one of the most important. We overplot the sensitivity curve for the proposed future space-based gravitational wave observatory LISA (signal-to-noise ratios of 1 and 5 in magenta and green, respectively, from Shane Larson’s sensitivity curve plotter), and BBO from Yagi & Seto (2017).

confirm or refute different ideas about what drives CE evolution, thus providing critical insight into CE physics.

It is certainly worth noting that, regardless of how the CE phase behaves in nature, MIC progenitors should be detectable in gravitational waves, in fact they could even be resolved, both in the Galaxy and the Magellanic Clouds. Though their birth rates will likely be lower in the Magellanic Clouds than in the MW owing to the smaller stellar mass of the LMC and SMC (Large and Small Magellanic Clouds), the fact that the LMC and SMC are more actively star forming (per unit stellar mass) means that the MIC birth rates may not be too far off from those we predict for the MW.

In Fig. 9, we show the gravitational wave strain amplitudes for different binary systems in our new CE model, noting that these results do not change significantly with adopted CE model. In this work, we have not attempted to replicate a sophisticated model of the MW in terms of star formation history and stellar density distribution. In reality, the gravitational wave signal will depend on not only the physical properties of a binary (as well as its distance), but will also involve assumptions about the instrument (and noise) itself. We plot the expected sensitivity curve for the future space-based gravitational wave observatory LISA for two signal-to-noise ratios and the expected sensitivity curve for the big bang Observatory (BBO). As a first-order approximation to the expected strain amplitude imparted by the population of MIC and AIC sources, we plot the strain amplitude for various binary systems with orbital periods less than 5.5 h at the current epoch assuming a distance of 8.5 kpc. We have again assumed a constant star formation history for 10 Gyr and an MW age of 10 Gyr with a total Galactic mass born in stars of $6.4 \times 10^{10} M_{\odot}$.⁴

⁴We note that the results shift up or down by a factor of ~ 10 and ~ 8 , respectively in terms of h , when distances of 1 and 50 kpc (LMC distance)

4 DISCUSSION

As mentioned previously, some formation channels require the CE phases to occur while the mass-losing star is only a slightly evolved giant, e.g. in the Hertzsprung Gap. However, the assumption that a binary can survive such a CE phase is rather optimistic. Stars in the Hertzsprung Gap have a more poorly defined core-envelope structure as compared to more evolved red giants or AGB stars that have a well-defined jump in specific entropy between the core and envelope (Belczynski et al. 2007). Further, stars that we have found to undergo significant mass loss (and initiate a CE phase), while in the Hertzsprung Gap may rather experience stable mass transfer instead (Pavlovskii & Ivanova 2015), which would change the evolutionary outcome of the binary altogether, likely lowering the number of potential MIC systems arising from certain formation channels.

As noted in Section 3, we do not produce any AIC NSs via the formation channel where a CO WD is produced first, then evolves into an ONe WD via accretion and subsequent carbon shell flashes, though we estimate the contribution from this channel to be on the order of 20 per cent. This COWD-to-AIC scenario was discussed in Brooks et al. (2017, see also Wang 2018), and Brooks et al. (2017) state that this may be a significant formation channel leading to AIC events. In our simulations, all AIC progenitors of ONe WDs have masses above $7 M_{\odot}$ on the ZAMS and, at the base of the AGB, their cores are above the minimum value (threshold between forming CO and ONe cores) that is needed to form an ONe WD (in STARTRACK). Our models predict some AIC systems that are similar to those considered in Brooks et al. (2017, an H-envelope-stripped helium-burning star donor with a mass $\sim 1.5 M_{\odot}$ when the final phase of pre-AIC mass transfer starts). The following example is found in our new CE model: the AIC progenitor’s evolutionary channel consists of several mass exchange events (including two CE events) with the final pre-AIC RLOF phase (between the H-envelope-stripped helium-burning star and the ONe WD) starting 47 yr after star formation. The AIC occurs just 0.5 Myr later (delay time 47.5 Myr). The NS + He star binary survives to later briefly re-establish stable RLOF between the H-envelope-stripped helium-burning star and the NS, (becoming an LMXB candidate), which continues even as the donor evolves off the helium main sequence (see also Liu et al. 2018). RLOF ceases at 61 Myr with component masses 1.44 and $0.71 M_{\odot}$, respectively, for the NS and evolved

are assumed. We show the entire simulated double WD population with grey circles and the MIC progenitor sub-population is overlaid with orange circles. In orange crosses, we show *post-AIC* binaries that are undergoing an LMXB phase, having since initiated a phase of RLOF between a WD and an NS. These plausible electromagnetic counterparts to post-AIC LISA binaries populate a similar region of parameter space as other mass-transferring double WDs, e.g. the AM CVn systems. In our simulation data, we do not find any post-AIC LMXBs that would currently be visible with LISA at the assumed distance (8.5 kpc), though the binaries with the highest gravitational wave frequencies (shortest orbital periods) start to be potentially visible around the SNR=1 curve when a distance of 1 kpc is assumed. We also note that Fig. 9 represents data from a simulation where the total simulated stellar mass was $1.63 \times 10^8 M_{\odot}$, which is a factor of 392 lower than the Galactic stellar mass. Due to the fact that we have not simulated the total number of stars in the Galaxy, combined with Monte Carlo effects, it may indeed be possible that a few to tens of post-AIC LMXBs could be detectable with LISA. An example of such a STARTRACK binary that appears with the highest gravitational wave frequency (one of the orange ‘x’ symbols in Fig. 9) is an HeWD + NS system with an orbital period of 34 min and estimated X-ray luminosity of $\sim 1 \times 10^{38} \text{ erg s}^{-1}$.

naked helium star. The helium star soon thereafter evolves into a CO WD and at this time the system has an orbital period of 125 min. Emission of gravitational radiation causes the NS–WD binary to merge 149 Myr after star formation. We note that this formation channel leading to a NS–WD binary merger is not found among the main four channels depicted in Toonen et al. 2018.

We find that in our simulations, AIC NSs that form at long delay times can exhibit properties that match those of so-called redback MSPs fairly well. Redbacks are binary MSPs with orbital periods shorter than about 1.5 d, low to zero eccentricities, and the pulsars’ companions have minimum masses estimated to be in the range $\sim 0.1\text{--}0.5 M_{\odot}$ (Smedley et al. 2015; Manchester et al. 2005). These systems exhibit long radio eclipses caused by circumbinary discs and do not lie on the $M_c\text{--}P_{\text{orb}}$ relation for MSPs that would be expected from the evolution of red giant donors later cooling to become He WD companions. Smedley et al. (2015) proposed that redbacks and some black widow pulsars could be the result of the AIC of an ONe WD. In STARTRACK, we find that those AIC systems that end up as non-accreting AIC NS + WD binaries with low-mass WD companions and short orbital periods (resembling observed redback systems) arise from different progenitor channels depending on the adopted CE treatment. Binaries exhibiting redback-like properties undergo AIC when the donor is on the main sequence, red giant branch or a helium WD in the classical CE model, and when the donor is a helium WD in the new CE model. Our current study clearly supports the (long delay time) AIC route for the formation of this exotic class of MSPs.

For over 80 per cent of AIC systems from our models, the companion star has evolved into a WD by a Hubble time. In cases where the companion is not a WD by a Hubble time it is almost always an H-envelope-stripped, helium-burning star (e.g. a CO WD progenitor). Observations (see Manchester et al. 2005) show that nearly 50 per cent of binary MSPs (about 60 per cent of the total population) have a helium-WD companion, 10 per cent a CO WD, 10 per cent are redbacks, and about 20 per cent have an ultralight companion (a substellar object or planet). Thus, our synthetic AIC population is in general agreement with current observations of MSPs, while the NSs forming via MIC will contribute to the population of isolated MSPs. We also note the formation of a few widely separated (though still bound) double NS binaries (separations of about $10^4 R_{\odot}$). In this case both ZAMS masses were in the narrow range $7.5\text{--}7.8 M_{\odot}$.

4.1 Impact of initial orbital configuration

We briefly discuss the general impact that adopting different assumptions for initial orbital distributions has on our results. Adopting the new CE model, we performed additional simulations adopting two different sets of initial distributions for orbital parameters. For one model, we used a thermal eccentricity distribution as adopted in Ruiter et al. (2009), and in another, we adopted the initial orbital period, eccentricity, and mass ratio distributions described in Sana et al. (2012). Hubble-time averaged AIC rates increased by 16 per cent when adopting the thermal eccentricity distribution, and decreased by 19 per cent when the Sana et al. (2012) distribution is adopted. For the MIC systems, in both cases the Hubble time-averaged rates increased by 37 per cent and 78 per cent, respectively.

A contributing factor to the boost in numbers of very close binaries (that will merge) in the model with a thermal eccentricity distribution is the fact that, for a small population of binaries that are initially eccentric, the orbit will not have circularized from tidal interactions before the first mass transfer phase takes

place. Evolutionary phases in STARTRACK that involve ongoing mass transfer assume circular orbital configuration, so for the small number of binaries that have not circularized by the time RLOF starts we set the binary separation to periastron position, thereby decreasing the orbital semimajor axis (a similar system but with $e_0 = 0$ would not ever get close enough to merge in a Hubble time). To an extent, this effect also plays a role for the Sana et al. (2012) model, but the assumptions for that model are quite different from our adopted model and the physical dependencies are more complex and harder to disentangle. The task of unravelling all of the outcome dependencies of how various assumptions alter the progenitor population is beyond the scope of this particular work, and such a parameter study would be a paper on its own (e.g. Claeys et al. 2014). It is worthwhile noting however that the total number of WD mergers is lower for the adopted model compared to the other two considered test models (this also applies to SN Ia progenitor candidates, e.g. CO + CO WD mergers, not just the heaviest WD mergers). Thus, our computed MIC birthrates could be seen as a lower limit – especially considering the fact that we have not included any double COWD binaries in our MIC calculations.

4.2 Globular clusters and the influence of initial helium fraction

We find that induced-collapse NSs can be born at any delay time ranging from ~ 30 Myr to a Hubble time and beyond (see Section 3.1). It has long been postulated that a low kick velocity channel for the production of NSs may be required to explain the large excess of these objects in globular clusters (Katz 1975). Core-collapse SNe may result in large natal kick velocities being imparted upon their newly formed NSs, owing to asymmetries that arise in mass ejection and/or neutrino emission (Janka 2017; Fryer & Kusenko 2006). MSPs derived from AIC are expected to suffer much smaller natal kicks than delivered to NSs resulting from core-collapse SNe (e.g. Freire & Tauris 2014, and references therein). This may help to explain how, despite their shallow gravitational wells, so many MSPs can be present in globular clusters (Grindlay 1987; Bailyn & Grindlay 1990; Benacquista, Portegies Zwart & Rasio 2001; Podsiadlowski et al. 2004; Ivanova et al. 2008; Freire 2013).

It is a worthwhile exercise to consider how different chemical environments can influence the formation of compact objects. In particular, enhancement of helium on the ZAMS can have a significant effect on the final evolution of the star – whether it evolves into a CO WD, ONe WD, or NS (Shingles et al. 2015). *Hubble Space Telescope* photometry has revealed that some metal-poor Galactic globular clusters host extremely helium-enhanced stellar populations, with helium abundances up to $Y \approx 0.4$ (Gratton, Carretta & Bragaglia 2012). An increase in helium for the Galactic bulge has also been suggested based on observations of the red giant branch bump (Nataf et al. 2011; Bensby et al. 2013) and the discrepancy between its photometric and spectroscopic turn-off ages (Nataf & Gould 2012). Helium-enhanced sub-populations have also been suggested for early-type and spiral galaxies (Atlee, Assef & Kochanek 2009; Chung, Yoon & Lee 2011; Rosenfield et al. 2012; Buell 2013).

While the effect of helium-enrichment on stellar evolution is relatively well known, e.g. the main-sequence luminosity will be higher owing to an increase in the mean molecular weight, most studies have focused on low-mass stars and the effect of helium enrichment on colour–magnitude diagrams (e.g. Sweigart 1987; Salaris & Cassisi 2005; Chantreau, Charbonnel & Decressin 2015). Single star models of intermediate mass that are evolved

past the main sequence also show interesting behaviour, with helium-enhanced models entering the AGB with a more massive H-exhausted core compared to their primordial helium counterparts (e.g. Karakas, Marino & Nataf 2014). The main consequence from that study is that the minimum mass for carbon burning is reduced from $>6M_{\odot}$ for $Y = 0.24$ down to $4\text{--}5M_{\odot}$ for $Y = 0.35\text{--}0.40$ for $[\text{Fe}/\text{H}] \approx -1.4$ (Shingles et al. 2015). In our simulations, we have adopted a canonical value for helium of $Y = 0.28$, similar to Karakas (2014). Interestingly, very metal-rich models of $Z = 0.1$ also show a decrease in the minimum mass for carbon burning to $\approx 7M_{\odot}$ compared to solar metallicity, a result which will be applicable to very metal-rich stellar populations including those found in massive early-type galaxies.

Because the stellar IMF (Kroupa et al. 1993) favours the production of lower-mass stars, the fact that the carbon-burning mass threshold can be decreased by up to two solar masses would have noticeable consequences. Larger initial helium abundances yield a larger number of ONe WDs and correspondingly, fewer CO WDs. Thus, the rate of SNe Ia from merging CO WD pairs would be decreased, as would the rate of SNe Ia involving RLOF toward a CO WD. At the same time, we would expect the rate of ONe production, and thus the AIC and MIC rates, to increase from the predicted Galactic rate of a few $\times 10^{-4}$ per year. This proposed effect might be somewhat curtailed if CO WD mergers on the lower mass end, e.g. even those WD pairs with combined masses below the Chandrasekhar mass limit, are an important contributor to SNe Ia (van Kerkwijk, Chang & Justham 2010). However, even though including the lower mass WD systems as potential SNe Ia progenitors brings the theoretical rate predictions into agreement with observations (Badenes & Maoz 2012; Maoz, Hallakoun & Badenes 2018), the idea is still somewhat speculative, since it remains to be demonstrated how the explosion would be triggered, and what the burning products might be.

5 SUMMARY

We have predicted birth rates, delay times, and progenitor configurations for NS production in binary star systems that contain at least one massive WD. We find that our AIC and MIC rates, calculated with the STARTRACK code, are in agreement with those found by Hurley et al. (2010, BSE code) and Lyutikov & Toonen (2017, SeBa code), respectively. Our present work substantiates the need to consider NSs formed via induced collapse as an important channel for NS formation. In the future, when WD binaries can be resolved through gravitational radiation, measuring their chirp masses should be possible, and with enough statistics these binaries will be useful in constraining their own evolutionary origin. As we have shown, it may be possible to set limits on CE physics by determining chirp masses of double WDs, since the two CE prescriptions adopted here exhibit distinct M_{chirp} distribution shapes (Figs 7 and 8). While MIC events are not expected to be detectable with LIGO, telescope array surveys like BlackGEM (Bloemen et al. 2015) should be able to detect optical counterparts of merging double WDs beyond our Galaxy. Such observations would be very useful for the successful gravitational wave detection of MIC binaries with LISA.

Particularly interesting results of our study are (1) a number of nearby MIC progenitor systems should be observable with sensitive space-based gravitational wave detectors such as LISA, (2) a smaller number of post-AIC systems that are undergoing a phase of RLOF between a WD and a NS could be observable with LISA and moreover should have electromagnetic counterparts as LMXB sources, (3) induced-collapse NSs can be born at extremely

early times after the onset of star formation, e.g. 30 Myr, as well as at extremely late times (Hubble time), and (4) in the AIC scenario, different types of donor stars are responsible for pushing the accreting WD toward the Chandrasekhar mass limit, and except for the AGB-wind donor case, AIC delay times reflect the evolutionary time-scale of the donor. In particular, if we allow a WD to accrete via a wind from an evolved (AGB) star, the AIC birth rates are noticeably enhanced, and a substantial fraction of these NSs are born with delay times <100 Myr (Figs 1 and 2). These AGB donor systems should be relatively bright, wide binary systems, but given the short-lived (~ 1 Myr) evolutionary phase and the current Galactic rate estimate for the AGB channel (3×10^{-5} per year), we only expect the MW Galaxy to currently harbour ~ 30 such systems. The hydrogen-stripped, helium-burning star donor channel, on the other hand, has an estimated Galactic birthrate of nearly 2×10^{-4} per year in the new CE model. The RLOF phase prior to the AIC event is short-lived ($\lesssim 0.1$ Myr), but the post-AIC, LMXB phase lasts on the order of 1 Myr. Thus, we estimate on the order of 200 such post-AIC accreting NS systems to exist in the MW, some of them potentially resolvable with LISA. If the duty cycle of such LMXBs is as high as 10 per cent, then ~ 20 of these systems are likely to be visible in the X-ray band and may be detectable with extended Roentgen Survey with an Imaging Telescope Array (eROSITA, see Predehl 2017); whether they are detectable with LISA depends crucially on their distance and orbital period (see Fig. 9). Though we leave detailed predictions of the future evolution of the entire AIC population for future work, we note that the He-star donor AIC channel is an important formation channel for producing NS + WD mergers (see also Toonen et al. 2018; Zenati, Perets & Toonen 2018).

We remind the reader that our simulations assume field evolution only, e.g. no N -body interactions, no triple evolution etc. N -body interactions are most important in dense environments, such as globular clusters, thus the rate estimates presented in this work are most relevant for the Galactic disc. Among higher stellar densities, stellar exchange interactions are likely to occur, which alters the evolutionary outcome of the stars. These additional interactions would likely lead to a higher number of AIC and MIC progenitor systems being created, which may be an important link toward understanding the formation of double NS mergers such as GW170817 (see Belczynski et al. 2018, fig. 3).

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APPENDIX

In this section, we describe the evolutionary pathway leading to the formation of MIC and AIC progenitors in more detail. We focus on four specific examples.

Example 1: Classical CE model, AIC, medium-long delay time: the following evolutionary example showcases the evolution of an AIC system that evolves into an NS + HeWD binary, though with an orbital period that is larger than those typical for redbacks. The ZAMS masses are 7.2 and 1.4 $M_{\odot}$ with a separation of 2310 $R_{\odot}$. The first interaction occurs at 53 Myr after starburst when there is a CE phase between the late AGB primary (5.8 $M_{\odot}$) and the main-sequence (1.4 $M_{\odot}$) companion. The CE phase causes the orbit to decrease from 1923 to 31 $R_{\odot}$ and the AGB core evolves into an ONe WD. The next interaction does not occur until 3409 Myr after starburst when there is stable RLOF between the red giant (1.4 $M_{\odot}$) secondary and the ONe WD (1.3 $M_{\odot}$). Mass transfer lasts a few Myr, initially proceeding on a thermal time-scale, until AIC occurs at 3411 Myr resulting in an NS (1.26 $M_{\odot}$) and the red giant is left with a mass of 0.96 $M_{\odot}$ (with a core mass of 0.25 $M_{\odot}$) with an orbital separation of 38 $R_{\odot}$ (18 d). A few Myr later, mass transfer is re-initiated when the red giant fills its Roche lobe again. Mass transfer ceases when the stars have attained an orbital separation of 150 $R_{\odot}$ (156 d) and the masses are 1.5 $M_{\odot}$ (NS) and 0.35 $M_{\odot}$ (red giant; core mass 0.32 $M_{\odot}$). The secondary shortly thereafter evolves into a helium WD (0.34 $M_{\odot}$). The system is found at a Hubble time with component masses 1.5 $M_{\odot}$ (NS) and 0.34 $M_{\odot}$ (He WD) with an orbital separation of 160 $R_{\odot}$.

Example 2: Classical CE model, MIC, very long delay time: we describe an example of a system that attains very high gravitational wave frequencies (final orbital period $\lesssim 10$ s of seconds or $f_{\text{gw}} > 0.08$; too rapidly evolving to be found in Fig. 9) at time of the WD–WD merger. The chirp mass of this system falls near the second peak in Fig. 7, at $M_{\text{chirp}} = 1.06$. The ZAMS masses are 8.5 and 7.0 $M_{\odot}$ with a separation of 62 $R_{\odot}$. Stable RLOF starts between the Hertzsprung Gap primary and the MS companion at 33 Myr post-starburst. RLOF continues until the orbital separation reaches 340 $R_{\odot}$ at which time-mass transfer ceases. By this time, the evolved primary is 1.7 $M_{\odot}$ and the secondary has attained a mass of 10.3 $M_{\odot}$. At 40 Myr, mass transfer is re-established between the H-envelope stripped (via previous mass transfer), helium-burning sub-giant which fills its Roche lobe and the MS secondary, and RLOF continues for a short time (< 1 Myr) until an orbital separation of 640 $R_{\odot}$. The primary shortly thereafter evolves into a CO WD. At 46 Myr, the secondary starts to evolve up the red giant branch, and at an orbital separation of 442 $R_{\odot}$, there is a CE between the red giant secondary and the CO WD. The system then consists of stars with masses 1.2 $M_{\odot}$ (CO WD), 2.3 $M_{\odot}$ (H-envelope stripped, He-burning star), and an orbital period of 3.9 $R_{\odot}$. The secondary shortly thereafter becomes an evolved H-stripped, He-burning star and initiates RLOF toward the CO WD primary at 50 Myr. Mass transfer steadily continues until the secondary evolves into an ONe WD. The MIC progenitor is found with an orbital separation of 3.9 $R_{\odot}$ and component masses 1.2 and 1.2 $M_{\odot}$ for the CO and ONe WD. The system loses orbital angular momentum due to gravitational wave emission and the stars merge at 10 097 Myr. We note that this system falls above the maximum threshold assumed for NS masses in Margalit & Metzger (2017), making it a viable stellar mass BH candidate.

Example 3: New CE model, MIC, short delay time: this system appears in the chirp mass distribution peak (see Fig. 8). In this short delay time channel example, the ZAMS masses are 7.4 and 5.2 $M_{\odot}$ with a separation of 818 $R_{\odot}$. The initial primary fills its Roche lobe while in the Hertzsprung Gap and the main-sequence secondary accretes matter stably, even after the primary evolves up the red giant branch. After the orbit has become very wide (445 d) mass transfer ceases, and soon after the primary becomes an H-envelope-stripped, helium-burning star. The secondary, now more massive than its ZAMS mass, becomes a red giant and when it fills its Roche lobe, mass transfer is unstable, and a CE phase follows. Upon emerging from the CE, the system consists of a double helium-burning star binary where both stars have lost their envelopes, e.g. a double sdB star (see Kupfer et al. 2015, for observed examples of similar, lower mass analogue systems), with an orbital period of 6.6 d and stellar masses of 1.27 and 1.91 $M_{\odot}$, respectively. Shortly thereafter, the primary evolves into a (helium) giant, and transfers mass stably to the (still compact) helium-burning star companion. After the primary evolves into a CO WD, and the secondary becomes a (helium) giant, the system soon encounters a second CE phase where, yet again, the secondary star loses its envelope (this time its helium-rich envelope). Upon emerging from

the CE, the binary consists of a CO WD and an ONe WD (masses 0.85 and 1.21 $M_{\odot}$, respectively) with an orbital period of 24 min.

Example 4: New CE model, AIC, short delay time: this example showcases a common channel in which the NS is formed via stable RLOF accretion on an ONe WD from the wind of an evolved AGB star. The stars start out on the ZAMS with masses 7.6 and 5.6 $M_{\odot}$ with an orbital separation of 6150 $R_{\odot}$. The primary evolves into an ONe WD at 47 Myr; by this time, the orbit has increased in size to 10 652 $R_{\odot}$ (stellar masses are 1.37 and 6.63 $M_{\odot}$). At 81 Myr post-starburst, the secondary becomes an evolved (thermally pulsating) AGB star (6.4 $M_{\odot}$; core mass 1.2 $M_{\odot}$), and at this stage, the ONe WD companion begins to accrete some mass lost in the AGB wind. By 82 Myr, the primary turns into an NS via AIC. The NS continues to accrete via the AGB wind, until the AGB star evolves into a CO WD (within 0.1 Myr). The final component masses are 1.28 and 1.23 $M_{\odot}$ for the NS and CO WD, respectively, on an orbit with separation of 24 d.

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