Does GW190425 Require an Alternative Formation Pathway than a Fast-merging Channel?

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Abstract

The LIGO/Virgo Scientific Collaboration (LVC) recently announced the detection of a compact object binary merger, GW190425, with a total mass of $3.4^{+0.3}_{-0.1}\,M_\odot$ and individual component masses in the range of about 1.1–2.5 $M_\odot$. If the constituent compact objects are neutron stars, then the total mass is five standard deviations higher than the mean of $2.66 \pm 0.12\,M_\odot$ for Galactic binary neutron stars. LVC suggests that the nondetection of such massive binary neutron star (BNS) systems in the Galaxy is due to a selection effect. However, we are unable to reconcile the inferred formation efficiency from the reported merger rate, $\mathcal{R}_{\rm GW190425} = 460^{+1050}_{-390}\,{\rm yr}^{-1}\,{\rm Gpc}^{-3}$, with predictions from our own study for fast-merging BNS systems. Moreover, the comparable merger rates of GW190425 and GW170817 are possibly in tension with our results for two reasons: (i) more massive systems are expected to have lower formation rates, and (ii) fast-merging channels should constitute $\lesssim 10\%$ of the total BNS systems if case BB unstable mass transfer is permitted to take place as a formation pathway. We argue that, to account for the high merger rate of GW190425 as a BNS system, (i) our understanding of NS formation in supernova explosions must be revisited, or (ii) more massive NSs must be preferentially born with either very weak or very high magnetic fields so that they would be undetectable in the radio surveys. Perhaps the detected massive NSs in NS–white dwarf binaries are our clues to the formation path of GW190425 systems.

Unified Astronomy Thesaurus concepts: Binary stars (154); LIGO (920); Neutron stars (1108); Common envelope binary stars (2156)

1. Introduction

Recently, the LIGO/Virgo Scientific Collaboration (LVC) announced the detection of a compact object merger with a total mass of $3.4^{+0.3}_{-0.1}\,M_\odot$, dubbed GW190425 (Abbott et al. 2020). The merger's total mass lies in a range in which each component can be consistent with being a neutron star. Prior to this detection, all the known binary neutron star (BNS) systems in the Galaxy occupied a very narrow range in mass, with a total mass of $\approx 2.66 \pm 0.12\,M_\odot$ (Farrow et al. 2019); the BNS system GW170817 with a total mass of $\approx 2.74^{+0.04}_{-0.01}M_\odot$ fell within this mass distribution as well (Abbott et al. 2017).

If GW190425 is a BNS system, it is critical to explain why such a massive BNS system has not been observed in the Galaxy to date. One possible explanation is the selection effects in the radio surveys. Such an oversight could arise if such massive binaries are preferentially formed with very short periods, and thus they have inspiral phases below 10 Myr. This will subsequently lead to severe Doppler smearing (Cameron et al. 2018), rendering their detection challenging. But does such a channel exist in nature?

BNS systems are thought to form through two distinct channels: field formation (Tauris et al. 2017; Chruslinska et al. 2018) and dynamical assembly (Ramirez-Ruiz et al. 2015), which is highly subdominant compared to a field formation channel (Ye et al. 2020). The field formation scenario predicts a delay time distribution that follows a power law (Dominik et al. 2012). However, a subpopulation of fast-merging systems can exist if unstable case BB mass transfer takes place in a common envelope (CE) between a He Hertzsprung gap (HG) star and an NS (Dewi & Pols 2003; Ivanova et al. 2003)

depending on the component masses and orbital separation. The outcome of such unstable Case BB mass transfer is uncertain; these systems enter into Roche-lobe overflow as He HG stars, and as such, the donor stars in these systems lack clear core-envelope boundaries. Recent work by Vigna-Gómez et al. (2018) does not rule out the existence of an unstable Case BB phase when accounting for the Galactic BNS population, yet a stable case BB is still preferred.

In this paper, we show that assuming GW190425 is a massive BNS system, the reported merger rate from LIGO/Virgo data is in tension with the expected merger rate of BNS systems born from fast-merging channels. In Section 2 we estimate the merger rate of systems similar to GW190425, assuming they arise from a fast-merging channel. In Section 3 we discuss the formation efficiency of such systems from population synthesis analysis. In Section 4 we argue that if GW190425 is a BNS system, its high merger rate implies massive NSs are born with a rate similar to their lower mass counterparts but they are systematically dimmer and therefore undetectable in the radio surveys. This can happen if these systems have either very low or very high magnetic fields. We summarize the results in Section 5.

2. Formation Rate of GW190425 Type Systems from Fast-merging BNS Systems

If systems such as GW190425 are products of fast-merging channels, the estimate of their merger rate is simplified because the delay time distribution is short enough that it can be ignored (Safarzadeh et al. 2019a). The star formation rate of the universe can be parameterized as a function of redshift as

(Madau & Dickinson 2014):

$$\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1 + ((1+z)/2.9)^{5.6}} \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3}. \quad (1)$$

We combine this with the analytic expressions for metallicity evolution used from Eldridge et al. (2019). The fractional mass density of comoving star formation below metallicity Z is given by:

$$\Psi\left(z, \frac{Z}{Z_\odot}\right) = \psi(z) \frac{\hat{\Gamma}[0.84, (Z/Z_\odot)^2 \, 10^{0.3z}]}{\Gamma(0.84)}. \quad (2)$$

In this equation $\hat{\Gamma}$ and Γ denote the incomplete and complete Gamma functions, respectively.

The merger rate of such massive BNS systems is therefore given by:

$$\mathcal{R}_{\text{GW190425}} = \lambda_{\text{f,BNS}} \Psi(0, Z) \times 10^9 \, \text{yr}^{-1} \, \text{Gpc}^{-3}, \quad (3)$$

where $\lambda_{\text{f,BNS}}$ is the formation efficiency that indicates the number of such systems born per unit solar mass of stars.

The reported value of $\mathcal{R}_{\text{GW190425}} = 460^{+1050}_{-390} \, \text{yr}^{-1} \, \text{Gpc}^{-3}$ (Abbott et al. 2020) translates into a range of $\lambda_{\text{f,BNS}} \approx 2.3 \times 10^{-4}$–$5 \times 10^{-3}$ if we assume that the progenitors of such systems have metallicities of $\lesssim 0.1 Z_\odot$ to have a total mass about the reported value (Giacobbo & Mapelli 2018) due to the fallback mechanism and electron capture supernovae. If we relax the assumption that low metallicity is needed to produce such systems (i.e., that the efficiency of massive BNS formation from case BB unstable mass transfer is insensitive to progenitor metallicity) we find $\lambda_{\text{f,BNS}} = 7.5 \times 10^{-6}$–$1.6 \times 10^{-4}$.

3. Formation Rate of Fast-merging BNS Systems in Population Synthesis Models

In Safarzadeh et al. (2019b) we analyzed formation models of BNSs from a StarTrack (Belczynski et al. 2002, 2006, 2008) population synthesis code to search for fast-merging channels. Three key parameters and therefore eight different models were analyzed. The first parameter concerns the behavior of binaries during a CE phase with an HG donor star; during a CE, an NS enters the envelope of its companion, exchanging orbital energy to unbind the donor's envelope (Fragos et al. 2019), and accretes only modest amounts ($\lesssim 0.1 \, M_\odot$) of envelope material in the process (MacLeod & Ramirez-Ruiz 2015). For giant stars, with a clear core-envelope boundary, the end result of this process (so long as there is enough orbital energy available to keep the system from merging) is a closely bound binary comprised of the accretor star and the giant star's core. However, HG stars lack well-defined cores, and studies are inconclusive as to whether binaries entering into a CE during this phase can survive without merging (Deloye & Taam 2010).

In one submodel (A), HG stars are treated such that a core could be distinguished from an envelope in their evolutionary phase; hence a successful CE ejection is possible. In the other submodel (B), any system entering into a CE with an HG donor is assumed to merge.

The second parameter studied was the natal kick received by an NS at birth. We analyzed models that adopted natal kicks randomly drawn from a Maxwellian distribution with $\sigma = 265 \, \text{km s}^{-1}$, based on the observed velocities of single Galactic pulsars (Hobbs et al. 2005), and models that adopt $\sigma = 135 \, \text{km s}^{-1}$.
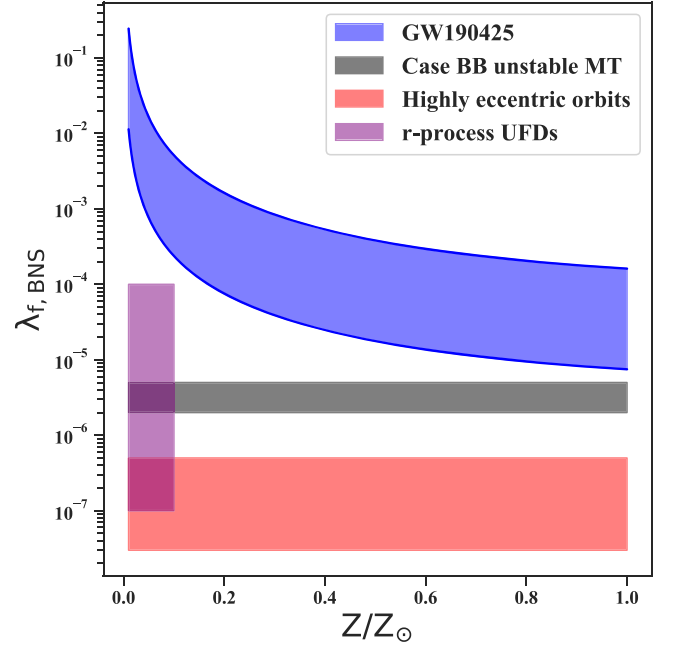

Figure 1. The inferred formation efficiency of massive BNS systems if GW190425 represents such a system (blue shaded region) and formed from a fast-merging channel in the field. The x-axis shows maximum metallicity below which such a formation channel could be active. The black and red shaded regions represent the fast-merging channel efficiency from population synthesis models. Two different submodels, A and B, have been analyzed, which treat the common envelope event with HG donor stars differently. In submodel A, the fast-merging BNS population comes from systems experiencing case BB unstable mass transfer (MT). In submodel B, the fast-merging channels are highly eccentric BNSs. The uncertainty in each band comes from different assumptions regarding the natal kicks of the neutron stars at birth and the metallicity dependence of the efficiency of the CE phase. The large formation efficiency required to account for GW190425 as a BNS system born out of a fast-merging channel is inconsistent with the formation efficiencies expected in the population synthesis models (Dominik et al. 2012). At low metallicities, the fast-merging BNS merger statistics should be compared to those of r-process enriched ultra-faint dwarf galaxies, which we show with a purple shaded region.

The third parameter we studied was metallicity, where we explored two different metallicities, $Z = Z_\odot$ and $Z = 0.1 \, Z_\odot$, for the BNS populations.

In submodel A, case BB unstable mass transfer makes up a population of fast-merging channel BNSs. In submodel B, the fast-merging channel comes from BNSs on highly eccentric orbits due to natal kicks in favorable directions. The summary of the analysis is presented in Figure 1.

The formation rate of fast-merging BNS systems is about $(2\text{–}5) \times 10^{-6} M_\odot^{-1}$ for submodel A where the range spans the uncertainty to the metallicity and natal kick assumptions. For submodel B the formation efficiency is about 3×10^{-8}–5×10^{-7}. Such small formation channels are inconsistent with the required large formation efficiency of $\lambda_{\text{f,BNS}} = 2.3 \times 10^{-4}$–$5 \times 10^{-3}$ inferred from GW190425 if this system is a BNS system formed through a fast-merging channel at low metallicities. Even if we treat the metallicity as a parameter with unknown impact, the absolute minimum efficiency of $\lambda_{\text{f,BNS}} = 7.5 \times 10^{-6}$ is still in tension with the efficiency range in population synthesis models of $\lambda_{\text{f,BNS}} = (2\text{–}5) \times 10^{-6} M_\odot^{-1}$.

However, we note that there is considerable uncertainty involved in population synthesis models, and one cannot, in the end, rule out the possibility that GW190425 was formed

through an unstable case BB mass transfer. For example, Romero-Shaw et al. (2020) suggest this as a formation scenario for GW190425, arguing that the helium progenitor star could explain the high mass of GW190425. While we have independently confirmed our results using the COSMIC[4] population synthesis model, we note that other groups have hinted that there are low rates of BNS mergers in the local universe, in general: for example, through a systematic study, Vigna-Gómez et al. (2018) shows that a scenario in which BB unstable mass transfer is modeled in their population synthesis code can lead to high local merger rates. However, one has to note that (i) such a model would be in tension with the distribution of the Galactic BNS systems (see their Figure A1), meaning not all the BNSs could experience this channel, and (ii) the study by Vigna-Gómez et al. (2018) is carried out at $Z = 0.0142$, and local star formation at such low metallicities is suppressed. Therefore, the predicted rates from this channel will be suppressed. Moreover, in a separate study, Neijssel et al. (2019) takes into account the uncertainty in the metallicity and star formation history of the universe and find a generally low local merger rate for BNS systems ranging from 10 to $300 \, \mathrm{yr}^{-1} \, \mathrm{Gpc}^{-3}$ (see their Table C.1). Therefore, if the rates coming from population synthesis are low, any subset of BNSs, e.g., a system similar to GW190525, will be predicted to have low merger rates as well.

Separately, models attempting to explain GW190425 as a fast-merging system need to be tested against the rarity of r-process enriched ultra-faint dwarf galaxies (UFDs): if the BNS merger rate from a channel active at low metallicities is high, it can lead to r-process enrichment of UFDs. However, of all the UFDs in the Galaxy, only about 20% are r-process enriched (Safarzadeh et al. 2019b). Through Poisson statistics of r-process sources in the early universe, Beniamini et al. (2016) showed that the formation efficiency per solar mass of stars formed should be within 10^{-7}–$10^{-4} M_\odot$. Based on our model, such formation efficiency at low metallicities falls short of explaining GW190425, since the star formation rate at such low metallicities is suppressed in the local universe. We show the expected efficiency of the fast-merging BNS system through the statistics of r-process enriched UFDs from Beniamini et al. (2016) in Figure 1.

We emphasize that the argument based on the rate of case BB unstable mass transfer presented in this work, though not refuting this formation path, casts doubt on its efficiency to explain GW190425, and further detailed work in support of or against our claim is needed.

4. Possible Solutions

Our goal in this paper is not to provide a progenitor solution but instead to test whether or not the presence of GW190425 can be accommodated within our current understanding. Here we discuss some plausible alternatives. Each possibility would require further calculations and simulations to be effectively tested, which is beyond the scope of this paper.

The lesson we learn from GW190425 is that nature makes BNS systems that are (i) massive and (ii) currently not observable in the radio sky as pulsars. These two points could be related. Such systems could reside in the graveyard parameter space in the period–period derivative distribution of known pulsars (see Figure 2).
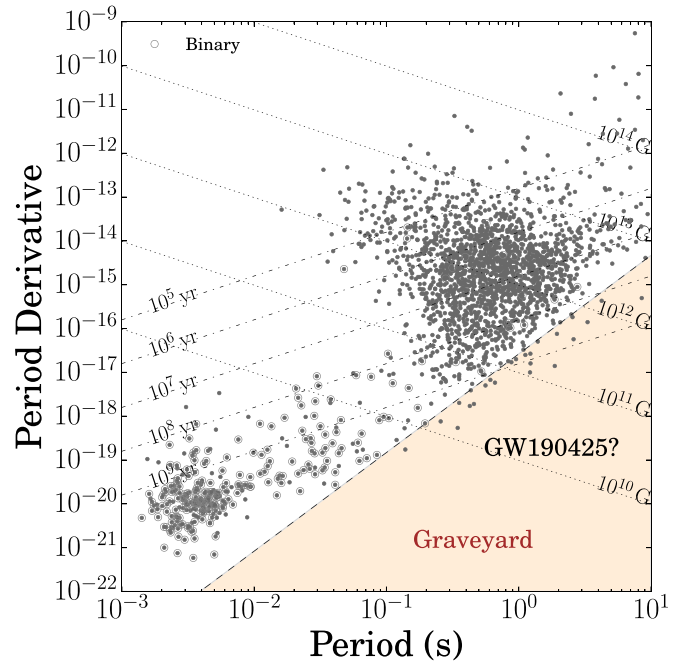
Figure 2. Distribution of known pulsars in the period–period derivative plane. Pulsars in binaries are shown with a circle. The graveyard is the region shaded with the brown color, where pulsars would not be detectable in radio sky. An NS can either be born in the graveyard or migrate there due to the spin down effect of its magnetic dipole moment. The timescale for the spin down can be very short for those with high magnetic fields. Since no binary neutron star is observed to be as massive as GW190425, it is possible that such massive binaries merge while being in the graveyard. This plot is made using the ATNF pulsar catalog (Manchester et al. 2005), and the PSRQPY Python package (Pitkin 2018).

We discuss possible scenarios that can produce massive BNS systems that have either very weak or very high magnetic field dipole moments, which will make them undetectable.

4.1. The Birth Magnetic Fields of Neutron Stars

Neutron stars are expected to rotate extremely rapidly and have strong magnetic fields due to the conservation of magnetic flux. The observation of several neutron stars, known as central compact objects (CCOs; Ho 2011), in supernova remnants with weaker magnetic fields than the average radio-pulsar population has motivated a lively debate about their formation. Can GW190425 be associated with this population?

The reported merger rate of double neutron stars from the LIGO VIRGO collaboration, $\mathcal{R}_{\mathrm{GW190425}} = 460^{+1050}_{-390} \, \mathrm{yr}^{-1} \, \mathrm{Gpc}^{-3}$, $\mathcal{R}_{\mathrm{GW170817}} = 760^{+1740}_{-650} \, \mathrm{yr}^{-1} \, \mathrm{Gpc}^{-3}$, is similar for the massive and light components.

In a recent study, Sukhbold et al. (2016) showed that a small percentage ($\lesssim 10\%$) of stars with masses between 18–120 $M_\odot$ could make NSs with masses greater than 1.6 $M_\odot$, while NSs with masses consistent with the observed galactic population could form from stars with masses between 10–18 $M_\odot$. Assuming a Salpeter initial mass function following $dN/dM \propto M^{-2.35}$, the relative expected formation rate of GW190425 to GW170817 type systems should be at least (conservatively) less than 10%. From this, we can conclude that the progenitor masses of these systems cannot be very different since the initial mass function of stars would have drastically impacted the expected merger rates. We note that our arguments are based on the inferred merger rate from a single

detection of GW190425-like systems. If future LVC observations show that the merger rate of GW190425-like systems is in fact smaller than GW170817-like systems, the above stated tension would be reduced.

One possibility is that the formation rate of heavier NSs is similar to standard NS formation. In order for these systems to be undetected, we would require that heavier NSs are born preferentially either inside the graveyard, such as CCOs, or with extremely large magnetic fields such that their radio-pulsar lifetime becomes extremely short.

CCOs might appear to be a natural candidate as they are likely NSs born with weak magnetic fields (Ho 2011), although fallback of the supernova debris onto the neutron star could have been responsible for the submergence of the field and its apparently low value. In such cases, resurfacing and emergence of the field could make these objects detectable. If born with a weak field, CCOs can only work as progenitors if they are more massive at birth than pulsars. If these systems are not born with higher masses, post-birth mass accretion is likely to spin them up to high, detectable luminosity, as we argue in the following section. Many issues about the nature of CCOs need to be settled before we can derive any firm conclusions.

4.2. Consequences of Significant Mass Gain

Mass accretion can take place during CE evolution, although estimates for the total mass accreted have been shown to be small (MacLeod & Ramirez-Ruiz 2015). Stable mass transfer through Roche-lobe overflow is another possibility. Yet, an NS accreting at the Eddington limit, $\dot{M}_{\rm Edd} \lesssim 10^{-8} M_\odot \, {\rm yr}^{-1}$ can accrete less than 0.1 $M_\odot$ in about 10 Myr, which is a conservative estimate for the lifetime of the companion. Assuming both neutron stars have 1.4 solar mass at birth, the first neutron star needs to accrete about 0.6 $M_\odot$ to bring the total mass of the binary to about 3.4 $M_\odot$. The accretion of this material will naturally lead to the NS spinning up and, as a result, the object luminosity will undeniably increase (Figure 2). If the magnetic field of the NS is large, it is feasible for the spin down timescale to be short, which might account for its potential disappearance.

Another opportunity to grow is by accreting fallback material from the supernova that gave rise to the last NS. The distribution of orbital separations for the pre-SN progenitor and the NS are poorly known (Ivanova et al. 2003) and it can range from hours to a few days. If the SN explosion is not as energetic, one can expect to accrete material that accumulates in a circumbinary disk (e.g., Schröder et al. 2018). In order for the NS to accrete 0.6 $M_\odot$ of fallback material, two properties need to be satisfied: the binary needs to be compact and the energy injected in the supernova needs to be no more than a few times the binding energy of the exploding He star, as demonstrated by Schröder et al. (2018).

This might happen only in a few cases, thus making it potentially difficult to still reconcile the merger rates of heavy systems with those from the standard channel.

One consequence of this super-Eddington mass accretion phase would be the subsequent burying of the magnetic field of the NS (Bernal et al. 2013), yet the field emergence timescale is likely to be significantly shorter than the merging timescale and the NSs will likely spin up as a result of accretion. Both effects will help increase the pulsar luminosity. As we argued before, only a very low or very high magnetic NS will be able to

appear undetected in our Galaxy if this channel was a prominent one.

In the end, the key unresolved issue is that we have serious deficiencies in our understanding of the magnetic field evolution and potential decay in pulsars. Past research attempting to constrain such initial distributions relied on the observed pulsar distribution in period–period derivative phase space in the Galaxy (Faucher-Giguère & Kaspi 2006; Osłowski et al. 2011). In this scenario the distribution of NSs in the $p - \dot{p}$ phase depends sensitively on assumptions relating to the decay of the magnetic field (Romani 1990; Cumming et al. 2001; Melatos & Phinney 2001; Choudhuri & Konar 2002; Payne & Melatos 2004). This is because the surface magnetic field strength of millisecond pulsars is found to be about 4 orders of magnitude lower than that of garden variety radio pulsars (with a spin of ≈ 0.5–5 s and $B \approx 10^{12}$ G). Without a clear understanding of this, we would be unable to make detailed predictions about the detectability of GW190425-like systems in the Galaxy.

5. Summary and Discussion

The LVC recently announced the detection of a compact object binary merger, GW190425, with a total mass of $3.4^{+0.3}_{-0.1}$ $M_\odot$. This system lies five standard deviations away from the known Galactic population of binary neutron stars (BNSs) with a mean total mass of $2.66^{+0.12}_{-0.12} M_\odot$. The comparable merger rate of this system to GW170817 raises several issues that we attempted to elucidate in this work.

The LVC speculates that such massive systems were not detected in previous radio surveys due to selection effects pertinent to far-merging channel BSNs. Assuming such systems are born from a fast-merging channel, namely, in the case BB unstable mass transfer, it would indicate that the delay time of such a system is extremely short (less than 10 Myr). To be consistent with the reported merger rate of GW190425 from LIGO O3 data ($\mathcal{R}_{\rm GW190425} = 460^{+1050}_{-390} {\rm yr}^{-1} \, {\rm Gpc}^{-3}$), one concludes that the efficiency of formation of fast-merging BNS systems should be between $\lambda_{\rm f,BNS} \approx 2 \times 10^{-4}$–$5 \times 10^{-3} M_\odot^{-1}$ depending on what we assume as the maximum allowable metallicity of their progenitor stars. However, we are unable to reconcile this with the formation efficiency of fast-merging BNS systems from the population synthesis models studied in this work which point to $\lambda_{\rm f,BNS} = (2$–$5) \times 10^{-6} M_\odot^{-1}$.

Moreover, the comparable merger rate challenges our understanding of supernova explosion in massive stars as more massive NSs are born from heavier progenitors such that the relative formation rate of massive to normal BNS systems should be at least suppressed by an order of magnitude.

Regardless of the issues above, if we assume our understanding of the supernova and fallback physics is subject to drastic modifications, we suggest that the only way to reconcile the observed rate with the lack of the previous detections of such systems in radio surveys is if these systems have suppressed the magnetic dipole moment. We argue a plausible solution could be that more massive NSs need to be preferentially born with either very weak or very high magnetic fields so that they would be undetectable in the radio surveys.

However, a caveat to this hypothesis is that we have seen massive NSs in white dwarf–neutron star (WD–NS) binaries (Kiziltan et al. 2013), such as J0740 + 6620. This means massive NSs are born with normal magnetic field strength in WD–NS systems and if our theory holds, it should be able to

account for this. Here we note that WD–NS systems can have different formation pathways, involving many episodes of mass transfer (Toonen et al. 2018) such that it is the WD that is born first, and then the NS. Extension of this work to WD-Ns would require modeling the magnetic field evolution in population synthesis studies of such systems, which is beyond the scope of our work.

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