

# Stellar Core-Merger-Induced Collapse: New Formation Pathways for Black Holes, Thorne - Żytkow objects, Magnetars and Superluminous Supernovae

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## ABSTRACT

Most neutron stars (NSs) and black holes (BHs) are believed to be the final remnants in the evolution of massive stars. In this study, we propose a new formation channel for the formation of BHs and peculiar NSs (specifically, magnetars and Thorne-Żytkow objects [TŻOs]), which we refer to as the core merger-induced collapse (CMIC) model. This model involves the merger during a common-envelope phase of an oxygen/neon/magnesium composition white dwarf and the core of a hydrogen-rich or helium-rich non-degenerate star, leading to the creation of peculiar new types of objects. The results of binary population synthesis simulations show that the CMIC channel could make important contributions to the populations of (millisecond) pulsars, TŻOs, magnetars and BHs. The possibility of superluminous supernovae powered by TŻOs, magnetars and BHs formed through the CMIC model is also being investigated. Magnetars with immediate matter surroundings formed after the CMIC might be good sources for fast radio bursts.

**Key words:** stars: evolution - (stars:) binaries (including multiple): close - (stars:) white dwarfs - stars: neutron - stars: black holes - (stars:) supernovae: general.

## 1 INTRODUCTION

The remnants of core-collapse supernovae (CCSNe) at the end of the evolution of single hydrogen-rich massive stars ( $\geq 8 M_{\odot}$ ) can be neutron stars<sup>1</sup> (NSs) or stellar-mass black holes (BHs) (e.g., Baade & Zwicky 1934; Woosley et al. 2002; Heger et al. 2003). There are also other formation pathways to form NSs and BHs, such as accretion-induced collapse (AIC) or merger-induced collapse (MIC) in interacting binaries: in the AIC channel, a white dwarf (WD) with an oxygen/neon/magnesium (ONeMg) composition or a NS accretes matter from a companion, the donor star, and grow in mass to a critical limiting mass (e.g., Michel 1987; Ivanova & Taam 2004; Ablimit & Li 2015) when they collapse to an even more compact state and become a NS or BH, respectively (e.g., Nomoto & Kondo 1991; Timmes et al. 1996). The merger of two WDs or the merger of two NSs may form NSs or BHs in the MIC pathway; these are also very promising sources for producing gravitational waves (GW) (e.g., Ivanova et al. 2008; Bauswein et al. 2013; Shapiro 2017; Lyutikov & Toonen 2019; Ruiter et al. 2019; Chattopadhyay et al. 2020; Abbott et al. 2020). The AIC route to form NSs is an important channel

to produce pulsars and magnetars (e.g., Hurley et al. 2010; Tauris et al. 2013; Ablimit & Li 2015; Jones et al. 2016; Ablimit 2019, 2022), including young pulsars in old populations (van den Heuvel 1981, 1987), and are promising contributors to the NS population in globular clusters because of their expected low kick velocities (e.g., Podsiadlowski et al. 2004; Ivanova et al. 2007). BHs formed through AIC or MIC may become members of low-mass or intermediate-mass X-ray binaries or even become single BHs (e.g., Belczynski & Taam 2004; Bauswein et al. 2013; Bernuzzi et al. 2020). The upper limit for the mass of NSs is a key parameter in these formation channels. However, the upper mass limit of NSs, above which they collapse to BHs, is still controversial due to poor observational constraints (e.g., Margalit & Metzger 2017).

In a binary, two stars can merge due to orbital angular momentum loss. Stellar mergers in binaries are important for a variety of astronomical phenomena, such as peculiar SNe, NSs and BHs. Indeed, a significant fraction of single massive stars may be the product of the merger of binary stars, and binary interactions, including mergers, are important for producing various types of SNe and unusual objects (e.g., Podsiadlowski et al. 1992; Langer 2012; de Mink et al. 2014; Andrews et al. 2018; Schneider et al. 2019; Horiuchi et al. 2020; Mandel et al. 2021). Wiktorowicz et al. (2019) studied possible merger routes to produce BHs by performing binary population synthesis (BPS) simulations. In the current study, we consider core

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<sup>1</sup> NSs also may be born through the electron-capture SNe (ECSNe from  $\sim 8 - 10 M_{\odot}$  main-sequence stars) (e.g., Miyaji et al. 1980).

mergers in WD binaries during the common envelope (CE) phase as an alternative pathway to form unusual objects including BHs.

Two stars evolve into a CE if mass transfer by Roche-lobe overflow in a binary is dynamically unstable (Paczynski 1976). Although CE evolution is still very poorly understood and not all binaries undergo the CE (e.g., Kemp et al. 2021), it has been seen as a crucial phase in binary evolution, irrespective of whether the stars merge in the CE or survive from the CE (see Ivanova et al. (2013) for a detailed review of the uncertainties and the importance of this phase). It has been suggested that future observations of planetary nebulae and luminous red novae may provide useful constraints to improve our understanding of many of the open questions of the CE phase (Blagorodnova et al. 2017; MacLeod et al. 2018; Jones 2020). Kruckow et al. (2021) presented a catalog of candidate post-CE binaries, and they showed that their catalog and its future extensions will provide insight into the evolution of close binaries through the CE phase. As long as a few decades ago, it has been suggested that the merger inside a CE could potentially trigger a peculiar supernova event (Sparks & Stecher 1974). The merger of a CO (carbon/oxygen) WD and the core of an asymptotic giant branch (AGB) star during the CE phase has been proposed as a possible progenitor channel for Type Ia SNe (e.g., Soker 2011; Soker et al. 2013). Mergers between WDs and cores of hydrogen-rich normal stars during the CE phase have been pointed out for the possible origins of intermediate-luminosity optical transients (Red Transient; Red Nova) and/or peculiar SNe (Sabach & Soker 2014). More recently, Ablimit (2021) investigated stellar core mergers between CO WDs and cores of hydrogen-rich intermediate-mass, cores of massive stars, or cores of helium-rich non-degenerate stars during the CE phase as origins for peculiar type Ia SNe and type II SNe with the framework of the core-merger detonation (CMD) model. The Galactic rates calculated with the CMD model show that this scenario has significant contributions to SNe Ia (i.e. overluminous/super-Chandrasekhar-mass SNe Ia and SNe Iax) and SN 2006gy-like type II superluminous SNe (SLSNe; see Ablimit (2021) for the details of CMD model and discussions).

The merger of a NS and the core of massive companion star inside the CE can produce a Thorne-Żytkow object (TŻO; Thorne & Żytkow 1977; Taam et al. 1978). TŻOs are an exotic class of stellar objects comprised of a neutron core surrounded by a extended envelope; from the outside they have the appearance of a red supergiant (Thorne & Żytkow 1977; Levesque et al. 2014; DeMarchi et al. 2021). They might eventually explode as (SLSNe)<sup>2</sup> (Moriya 2018; also see Chevalier (2012)<sup>3</sup>). Magnetars and accreting BHs have also been studied as potential central engines for powering SLSNe (Kasen & Bildsten 2010; Woosley 2010; Inserra et al. 2013; Dexter & Kasen 2013). In this study we consider a possibly important (see our results and discussions for important contributions of the channel to peculiar transients and objects), alternative channel for producing SLSNe, involving TŻOs, magnetars and BHs.

Here, we systematically explore the presumed core-collapse SN-like event following the merger of an ONeMg WD and the core of a non-degenerate star inside a CE. We call this channel, involving the merger of a ONeMg WD with the He core of a massive star in a CE, the core merger-induced collapse (CMIC) scenario in order to distinguish it from the more ‘normal’ AIC because the timescale of

CMIC is much shorter than the timescale of AIC in accreting ONeMg WDs through stable mass transfer. We propose that the CMIC scenario could be an alternative formation channel for single (millisecond) pulsars, magnetars and BHs with an accretion disk, and that SLSNe could be powered by these compact objects formed through CMIC. We also study the mergers between ONeMg WDs and cores of stripped, non-degenerate helium stars and low-/intermediate-mass stars as a potential channel to produce single (millisecond) pulsars. The rates of ONeMg WD – NS binaries surviving the CE phase are also being investigated as they are potential GW sources. We also explore how the final outcomes of these binary populations depend on the modeling of the more poorly understood physical phases and key parameters in binary evolution studies, specifically involving mass transfer (e.g., its stability depending on the mass ratio and the mass-transfer efficiency), the modeling of the common-envelope phase (e.g. the CE efficiency and the binding energy parameter), metallicity, etc. In §2, we describe our method to treat the physical binary processes in the BPS simulations and discuss the assumptions for the CMIC. The main results are presented in §3. The possible contribution and possible observational implications are discussed in §4, and a summary is given in §5.

## 2 METHODS

### 2.1 Binary Model Set

In order to derive the population of WD+non-degenerate star binaries, we perform Monte-Carlo simulations by using an updated *BSE* population synthesis code based on Hurley et al. (2002; see Ablimit et al. (2016) and Ablimit & Maeda (2018) for the updated version), starting with  $10^7$  primordial binaries (consisting of two zero-age main sequence stars) with chosen distributions of primary mass, secondary mass and orbital separation. Initial binary parameters of primary mass, secondary mass and orbital separation can be set up with the  $n_x$  grid points of parameter  $\chi$  logarithmically spaced,

$$\delta \ln \chi = \frac{1}{n_x - 1} (\ln \chi_{\max} - \ln \chi_{\min}), \quad (1)$$

For each set of initial parameters, we evolve the binary system to an age of the Hubble time, or until it is destroyed. Each phase of the evolution, such as tidal evolution, angular momentum changes due to mass variations etc., is followed in detail according to the algorithms described in Hurley et al. (2002). The initial input parameters of the primordial binaries are set the same as in Ablimit et al. (2016). The initial mass function of Kroupa et al. (1993) is adopted for the primary star ( $M_1$ ),

$$f(M_1) = \begin{cases} 0 & M_1/M_\odot < 0.1 \\ 0.29056(M_1/M_\odot)^{-1.3} & 0.1 \leq M_1/M_\odot < 0.5 \\ 0.1557(M_1/M_\odot)^{-2.2} & 0.5 \leq M_1/M_\odot < 1.0 \\ 0.1557(M_1/M_\odot)^{-2.7} & 1.0 \leq M_1/M_\odot \leq 150, \end{cases} \quad (2)$$

The distribution of the mass of the secondary ( $M_2$ ; where the secondary is the star with the lower initial mass) is determined by the distribution of the initial mass ratio,

$$n(q) = \begin{cases} 0 & q > 1 \\ \mu q^\nu & 0 \leq q < 1, \end{cases} \quad (3)$$

where  $q = M_2/M_1$  and  $\mu$  is the normalization factor for the assumed power-law distribution with index  $\nu$ . We consider a flat distribution ( $\nu = 0$  and  $n(q) = \text{constant}$ ) for the initial mass-ratio distribution.

<sup>2</sup> Superluminous SNe (SLSNe) have a luminosity around  $10^{44}$  erg s<sup>-1</sup> and radiate a total energy of  $\sim 10^{51}$  erg over a period of several months (see Moriya et al. (2018a) and Gal-Yam (2019) for reviews). Type I SLSNe do not show hydrogen lines in their spectra, while Type II SLSNe do.

<sup>3</sup> In Chevalier’s paper, the SLSN occurs in the spiral-in process itself, in a TŻO.

The chosen distribution for the initial orbital separation,  $a_i$ , is

$$n(a_i) = \begin{cases} 0 & a_i/R_\odot < 3 \text{ or } a_i/R_\odot > 10^6, \\ 0.078636(a_i/R_\odot)^{-1} & 3 \leq a_i/R_\odot \leq 10^6. \end{cases} \quad (4)$$

We also adopt a thermal distribution for the initial eccentricity between 0 and 1. For the SN remnant calculation, we adopted the rapid remnant-mass model of Fryer et al. (2012) in the subroutine *hrdiag* of the updated *BSE* code, and note that a typo in Fryer et al. (2012) has been corrected in our code (corrected as  $a_1 = 0.25 - 1.275/(M_1 - M_{\text{proto}})$ ), and the proto-compact object mass is set as  $M_{\text{proto}} = 1.0M_\odot$ ). For the natal supernova kick velocity, imparted to the newborn NS at its birth, we adopt Maxwellian distributions with a velocity dispersion of  $\sigma_k = 265 \text{ km s}^{-1}$  (Hobbs et al. 2005) for CCSNe and  $\sigma_k = 40 \text{ km s}^{-1}$  for ECSNe/AIC (e.g., Hurley et al. 2010). For the wind mass loss, the prescription of Vink et al. (2001) is used for O and B stars in different stages (hot stars), and  $1.5 \times 10^{-4} \dot{M}_\odot \text{ yr}^{-1}$  for luminous blue variables (Vink & de Koter 2002) in the subroutine *mlwind* of the code (see the wind model 2 of Ablimit & Maeda (2018)). Note that these prescriptions (for massive stars), i.e., the remnant-mass determination, wind mass loss and kick velocity do not influence the main results of this study as the formation of the ONeMg WD systems of interest here never suffer from CCSN explosions nor do they involve very massive stars. One of the important issues is how ONeMg WD form. Stellar evolution remnants composed mainly of O and Ne after the ejection of the envelope of a thermally pulsing AGB stars are considered as ONeMg WDs in the code (e.g., Hurley et al. 2000). Note that the mass range of stars that form ONeMg WDs strongly depends on the modeling of a variety of, sometimes uncertain, processes in stellar evolution codes, such as the initial composition, the adopted overshooting, nuclear reaction rates and the role of rotation (e.g., Doherty et al. 2017).

As discussed in section 1, CE evolution is a key phase in the evolution of many binary systems. Whether it occurs depends most importantly on the mass ratio. If the mass ratio is larger than a critical mass ratio ( $q_c$ ), mass transfer between the two binary components is dynamically unstable and a CE forms. When the donor star is on the main sequence (MS) or crosses the Hertzsprung gap (HG), our adopted default value is  $q_c = q_{\text{const}} = 4.0$  (Hurley et al. 2002). As an alternative we also use a prescription of  $q_c = q_{\text{cs}}$  in the subroutine *evol2* of the code, where  $q_{\text{cs}} = M_1/M_2$  is determined with the mass-transfer model by taking the spin of the accretor into account (for more details see Ablimit et al. (2016) and Ablimit & Maeda (2018), and see Table 2). This rotation-dependent mass accretion model leads to the accretion efficiency, because the accretion rate of a rotating accretor is reduced by a factor of  $(1 - \Omega/\Omega_{\text{cr}})$ , where  $\Omega$  is the angular velocity of the star and  $\Omega_{\text{cr}}$  is its critical rotation value (e.g., Stancliffe & Eldridge (2009)). An accreting star can spin very rapidly even when only a small amount of mass has been transferred from the donor (Packet 1981); this drastically reduces the mass-transfer efficiency (to values  $< 0.2$ ) and can even stop it completely when the accretor rotates at  $\Omega_{\text{cr}}$  (but also see Paczyński (1991)). The mass-transfer efficiency determines how much of the transferred matter is accreted by the accretor and how much escapes from the binary. It is assumed that the matter is escaped/ejected from the binary when it is no longer affected by the binary. We assume that material that is ejected from the system carries the specific angular momentum of the accretor (e.g., Hurley et al. 2002). In this prescription, the maximum initial mass ratio of the primary to the secondary in the primordial binaries can be as high as  $\sim 5$ -6, and a larger number of primordial binaries can avoid a contact phase and hence experience stable mass transfer until the primary's envelope is completely exhausted (see

Abdusalam et al. (2020) for similar discussions and results). When the original primary is on the first giant branch (FGB), AGB or is a helium (He) star, the prescriptions in Hurley et al. (2002) are applied.

The standard CE model, based on energy conservation (Paczynski 1976; Ivanova 2013), is utilized in our simulations,

$$E_{\text{bind}} = \alpha_{\text{CE}} \Delta E_{\text{orb}}, \quad (5)$$

where  $E_{\text{bind}}$  and  $\Delta E_{\text{orb}}$  are the binding energy of the envelope and the change in the orbital energy during the CE phase, respectively. In the specific model of Webbink (1984), which we adopt here, the binding energy of the envelope is parameterized as,

$$E_{\text{bind}} = -\frac{GM_1 M_{\text{en}}}{\lambda R_1}, \quad (6)$$

where  $M_1$ ,  $M_{\text{en}}$  and  $R_1$  are the total mass, envelope mass and radius of the primary star, respectively. We use two values for the CE efficiency as  $\alpha_{\text{CE}} = 1.0$  and  $\alpha_{\text{CE}} = 0.1$  in the subroutine *comenv* of the code. The value of  $\lambda$  varies when a star evolves and strongly depends on the star's initial mass, its evolutionary state and other possible energy sources, such as, e.g., recombination energy (see, e.g., Han et al. 1994; Tauris & Dewi 2001; Podsiadlowski et al. 2003; Wang et al. 2016a,b). The results of Wang et al. (2016a,b) are supported by Klencki et al. (2021), they are also consistent with results of the very recent CE study of Vigna-Gómez et al. (2021), and these consistency show the fact that results of Wang et al. (2016a,b) are the correct and reliable ones. We take either a constant value  $\lambda = 0.5$  or the detailed prescription  $\lambda = \lambda_w$  ( $\lambda_w$  is taken from  $\lambda_b$  of Wang et al. (2016b)) for the binding energy parameter. Whether the two stars merge completely or survive from the CE to continue their evolution critically depends on these two parameters. We set the initial metallicity of stars to be  $Z = 0.02$  and  $Z = 0.001$ . Table 2 summarizes our main simulation models. For other parameters we use the default values in Hurley et al. (2000, 2002).

## 2.2 The Core Merger-Induced Collapse during the CE phase

In the traditional AIC scenario, the ONeMg WD grows towards the Chandrasekhar mass by accreting H- and/or He-rich material transferred from its non-degenerate companion through stable mass transfer. In addition to the AIC channel, two WDs in a compact binary (with a combined mass  $\geq$  the Chandrasekhar mass where at least one of them is an ONeMg WD) may merge and collapse to a NS in the so-called merger-induced collapse (MIC). Because the energy released by nuclear fusion in a O+Ne deflagration that is expected to take place during the merging process is not sufficient to cause an explosion of the tightly bound core (Miyaji et al. 1980), further electron captures eventually lead to the gravitational collapse of the core and the formation of a NS (e.g., Nomoto & Kondo 1991). AIC/MIC is the favored alternative way to produce pulsars in globular clusters that have characteristic ages significantly less than the age of the clusters (Lyne et al. 1996; Boyles et al. 2011), and also to form millisecond pulsars (MSPs) in addition to the standard recycling scenario involving NSs formed in a CCSN (Chanmugam & Brecher 1987; Michel 1987; Kulkarni & Narayan 1988; Bailyn & Grindlay 1990).

In this work we consider the case where, after a ONeMg WD CE system formed, the two cores, i.e. the WD and the core of the donor star, spiral towards each other; if the CE cannot be expelled, they eventually coalesce and mix completely when the cores are both degenerate. If one core is considerably more compact (usually a WD) than the other (e.g. a non-degenerate He core), the non-degenerate component will eventually be tidally disrupted. The WD will sink

to the center of the CE system without mixing, while it rapidly accretes material from the disrupted component. In both cases, the final outcome will be the collapse of the WD to form a more compact object. We present several evolutionary routes involving a CE phase, assuming that the CMIC happens inside the CE if the combined mass of an ONeMg WD and the core mass of the companion star is larger than the Chandrasekhar limit mass ( $1.44M_{\odot}$ ).

How the final merging of the compact core and the companion object happen is not very well understood, and it is not entirely clear whether and how the core is being spun up, but there are various possibilities for spin-up. For example, the matter stream of the spiraling-in companion may impact with the more compact core and spin it up in a "slow merger" phase (e.g., Podsiadlowski et al. 2010). Another possibility is that the spiral-in occurs on a dynamical timescale and the companion is immediately dynamically disrupted; this would naturally lead to some type of accretion disk around the more compact component from which it could be spun-up by disk accretion.

If the combined core masses are larger than  $1.44M_{\odot}$  and the total mass (the two cores and the envelope) is less than  $15 M_{\odot}$  during the CE, the core merger through the CMIC could form NSs/pulsars (of which a fraction could be MSPs) or magnetars (see Figure 1 as one example; this will be further discussed in subsequent sections). The newborn NS formed by CMIC is likely to be surrounded by a substantial amount of material because not all the CE material may be ejected from the newborn NS in the collapse event<sup>4</sup>. Here, the newborn NS formed from CMIC in the WD + massive star binary could be an unusual type of object, because this NS would be surrounded by a very massive envelope, potentially much more massive than the central compact object itself. Thus, this would produce a configuration similar to that of a TZO (e.g., DeMarchi et al. 2021); we therefore postulate that TZOs could be formed in the CMIC scenario.

As the envelope loses its thermal energy by radiation from the surface of the merger product, an accretion disk may form around the compact core, in particular as neutrino cooling could be very effective near the NS (e.g., Fryer et al. 1996; Taylor et al. 2011). Fryer et al. (1996) predicted that a range of rapid-infall neutron star accretors present in certain low-mass X-ray binaries, common-envelope systems, cases of supernova fallback, and TZOs would lead to explosions by neutrino heating similar to the neutrino-driven explosions in standard CCSNe.

A certain fraction of known WDs in binaries has been found with bipolar magnetic fields (Kahabka 1995; Sokoloski & Bildsten 1999; Osborne et al. 2001; Ferrario et al. 2015; Pala et al. 2020), and some observed WDs are highly magnetized (e.g., Schmidt et al. 1999). The magnetic field of a WD has been pointed out as one important physical parameter that influences the evolution of a WD in a binary (e.g., Wheeler 2012; Ablimit et al. 2014; Farihi et al. 2018). Recently, detailed and systematic binary evolution studies show that the magnetic field of the WD can affect the accretion phase (Ablimit & Maeda 2019a, b), and Ablimit (2019) showed that it can play a crucial role in the AIC formation route for peculiar MSPs. A magnetic WD can be spun up by gaining angular momentum during the merger process inside the CE as discussed above. If the WD in the CMIC channel is strongly magnetized, the newborn MSP/pulsar would in-

herit the large magnetic field through magnetic field amplification during the CMIC process of the highly magnetized WD (e.g., Duncan & Thompson 1992). Indeed, several previous studies proposed that the large magnetic fields of magnetic WDs can be formed or amplified during CE evolution (e.g., Tout et al. 2008; Wickramasinghe et al. 2014; Ohlmann et al. 2016). Based on these observational and theoretical studies, we here hypothesize that a magnetar could be the result of this CMIC formation channel if it formed in a WD CE system with a highly magnetized WD.

The first magnetar was identified about three decades ago; typically magnetars are isolated and relatively rapidly rotating neutron stars (NSs) with very strong magnetic fields (up to  $\sim 10^{15}$  G; Duncan & Thompson 1992). The majority of the magnetars known to date (29 in the compilation of Olausen & Kaspi (2014)) have been discovered just over the past two decades (with a range of spin periods between 1 and 11 s) through their distinctive high-energy phenomenology: bursts of X-ray/gamma-ray emission and/or enhancements of their persistent X-ray luminosity, dubbed 'outbursts' (see Kaspi & Beloborodov 2017; Esposito et al. 2021). A magnetar surrounded by ejected material in this channel may power X-ray emission and possibly 'outbursts'. It is also possible that a BH may be formed in a CMIC during the CE phase when the combined core masses are larger than  $1.44M_{\odot}$  and the total mass (cores and envelope) is larger than  $15 M_{\odot}$ ; the reason why we set  $15 M_{\odot}$  as a cut to form pulsars/magnetars or BHs will be discussed further in subsections below (especially in subsection 3.2). The possibility that the central newborn objects, such as TZOs/magnetars/BHs, may power transient events like SLSNe will also be considered in later sections.

### 3 RESULTS

We first examine the evolution of two MS stars leading to a CE event involving an ONeMg WD and the core of a non-degenerate star. In a Monte-Carlo simulation of  $10^7$  binaries with the standard model parameters (model 1), there are 3535 CE events which involve ONeMg WDs and non-degenerate stars, and 1907 of them end up with mergers between the ONeMg WDs and the cores of the non-degenerate stars inside the CE. We focus on the core mergers during the CE phase as progenitors of some transients and objects and considering different binary stellar physics assumptions to estimate the importance of the different channels.

#### 3.1 Pulsars, Thorne - Żytkow object, Magnetar and Superluminous SNe through CMIC inside the CE

In a typical example, illustrated in Figure 1, the primary star evolves through the MS, HG, helium-rich MS (HeMS) and helium-rich giant (HeG) phases and forms an ONeMg WD<sup>5</sup>. Because of the two stable RLOF mass-transfer phases from the primary, the secondary becomes a relatively massive star. The WD is engulfed by the mass gained from the massive secondary when the secondary fills its Roche lobe during its core helium burning (CHeB) stage. The system fails to eject the CE, and the WD and the core of the massive secondary merge during the CE phase. This evolutionary route of the merger between an ONeMg WD and the core of a H-rich normal star finally produces a NS. The large amount of angular momentum transferred

<sup>4</sup> For comparison, only 10% of the envelope typically becomes unbound when MS stars merge (e.g., Owocki et al. 2019), and the unbound ejecta is probably around 1% for degenerate mergers (e.g., see Fig. 13 in Dan et al. (2014)).

<sup>5</sup> Note that the mass of zero-age MSs to form ONeMg WDs may be different (comparing to single stellar evolution) due to possible early mass loss or accretion caused by the binary interaction (e.g., Hurley et al. 2000, 2002).

onto the compact object during the merger process may make the newborn NS a fast rotator like a pulsar or a millisecond pulsar. If the WD has a strong magnetic field before the merger, the newborn NS most likely would become a magnetar.

The typical ranges of the initial binary parameters for the ONeMg WD + H-rich star CE event channel are: initial primary masses,  $M_{1,i} \sim 6.3 - 11.0M_{\odot}$ , secondary initial masses,  $M_{2,i} \sim 1.0 - 10.2M_{\odot}$ ; initial orbital periods,  $P_{\text{orb},i} \sim 0.01 - 122.0$  days. Figure 2 shows the mass distributions in model 1 for the merger case which cause CMIC. Compared to the initial binary parameters of all ONeMg WD + H-rich star systems with a CE, the initial conditions (mass ranges) of binaries that lead to the core merger during the CE are quite similar (Figure 2). Figure 2 shows that mergers with more massive donors generally have a larger CE mass.

The rates of all ONeMg + non-degenerate star systems associated with a CE and core merger events for the different models considered are summarized in Table 3. Table 3 shows that the rates of all ONeMg WD + non-degenerate H-rich star CE events vary significantly with the  $\alpha$  parameter, metallicity and mass transfer assumptions. The pessimistic value of  $\alpha = 0.1$  in model 2 causes more mergers between non-degenerate stars during the CE events, therefore the number of ONeMg WD binaries with CE phases are reduced from 0.33% to 0.15%. The model with the pessimistic value  $\alpha = 0.1$  is adopted for illustrating the effect of  $\alpha$ , though it should be noted that with such a pessimistic value, no close double NS systems as GW sources can be formed (see Table 3). For all merger cases (0.005% - 0.20% mergers of  $10^7$  binaries), more binaries can have stable mass transfer and avoid the CE phase with the mass-transfer (critical mass ratio) model adopted in model 5 (see Section 2), thus reducing CE events in general. Because more energy (i.e. internal energy) is considered in the  $\lambda$  prescriptions of models 4 and 5 for the CE expulsion, there are more successful CE ejections in the binaries, which reduces the number of CE merger systems. Zapartas et al. (2017) studied mergers of ONeMg WDs and HG stars as a contributor to 'late' core-collapse SNe, and their rate ( $\sim 2.1 \times 10^{-4}M_{\odot}^{-1}$ ) is in good agreement with our rate derived with mergers of ONeMg WDs and normal stars ( $\sim 1.9 \times 10^{-4}M_{\odot}^{-1}$ ; see R1 or R3 in line 2 of Table 3). In this work, we investigated more new pathways as origins of various transients and peculiar objects comparing to literatures.

Now first consider cases with condition (1), i.e., systems with a combined core mass  $M_{\text{com}} \geq 1.44M_{\odot}$  and total mass  $M_{\text{all}} < 8.0M_{\odot}$  for mergers during the CE phase. This includes mergers between ONeMg WDs and He cores of evolved hydrogen-rich stars, and also mergers between ONeMg WDs and degenerate cores during the late stages of AGB stars (e.g., Canals et al. 2018). The evolutionary delay times in this channel range from  $\sim 0.1$  to 12.5 Gyr. The rates for these systems range from  $0.24 \times 10^{-5}M_{\odot}^{-1}$  to  $7.38 \times 10^{-5}M_{\odot}^{-1}$  for the different models in Table 3. The newborn NSs with condition (1) could be MSPs with relatively smaller envelope mass (see Section 2 for the discussion of formation pathway, and Figure 2). Derived rates with CMIC are consistent with rates of AIC in previous studies (e.g., Hurley et al. 2010; Ablimit 2022).

Mergers with condition (2) (i.e.  $M_{\text{com}} \geq 1.44M_{\odot}$  and  $8.0 \leq M_{\text{all}} < 15.0M_{\odot}$ ) tend to form NSs surrounded by a large amount of material because of the more massive CE (see the discussion in Figure 2). As discussed in Section 2, newborn NSs surrounded by massive envelopes naturally produce TZO. The typical TZO formation rate from the CMIC channel is  $\sim 6 \times 10^{-5} \text{ yr}^{-1}$  if we adopt a star-formation rate of  $2 M_{\odot} \text{ yr}^{-1}$  (e.g., Misiriotis et al. 2006; Robitaille & Whitney 2010) and binary fraction of 0.7; our rate is lower than the rate of  $\sim 2 \times 10^{-4} \text{ yr}^{-1}$  estimated by Podsiadlowski et al. (1995). The evolutionary delay times in this channel are between

$\sim 14.18$  and  $86.22$  Myr. If we consider systems with a total mass  $M_{\text{all}} \geq 10.0M_{\odot}$  for producing TZO, the Galactic rate from the CMIC channel would be one order of magnitude lower than the estimate of Podsiadlowski et al. (1995), and these TZO may evolve into other objects on a relatively short timescale. TZO born here would have very massive envelope (often larger than  $8M_{\odot}$ ). Moriya (2018) has studied the strong accretion that occurs onto the central neutron core when the nuclear reactions that support such massive TZO terminate. As the accretion is neutrino driven, it can be highly super-Eddington and trigger a supernova event when the NS contracts and ultimately collapses. Such explosions would be observed as energetic Type II supernovae or even as superluminous supernovae of Type II. A strong large-scale outflow or a jet can be launched from the super-Eddington accretion disc formed during the collapse (Moriya 2018). The fallback of material towards the neutron star after a successful explosion is large in this case, and a black hole is formed very quickly (i.e. a few seconds; Fryer et al. 1996).

With conditions (1) and (2), it is possible that the newborn NSs/pulsars/MSPs formed through CMIC could be magnetars if the collapsing WDs are strongly magnetized (as discussed in section 2). The fraction of highly magnetized WDs among the WD population has been estimated from observations to be around 15% ( $\sim 15\%$ - $18\%$ ; Ferrario et al. 2015; see also Kepler et al. 2013, 2015). Adopting 15%, we can estimate a possible birthrate for magnetars via CMIC. It lies between  $0.03 \times 10^{-5}M_{\odot}^{-1}$  and  $2.46 \times 10^{-5}M_{\odot}^{-1}$  for the different chosen models (see Table 3). Note that these rates are simply obtained by combining the results for conditions (1) and (2) and multiplying them with 0.15. These rates have a good agreement with the Galactic rate of magnetars formed by AIC from magnetized WD binaries (Ablimit 2022). A rotating magnetar radiating according to the classic dipole formula could power a very luminous supernova (e.g., Woosley 2010); thus magnetars formed via CMIC may power Type II SLSNe. We will compare the predicted rates with observationally inferred rate of peculiar SNe in Section 4.

The combined total mass distributions (Figure 3) for mergers demonstrate that metallicity, the details of mass transfer and the binding energy parameter in the CE phase play an important role. The central temperatures and densities are higher, and more hydrogen burns stably for the lower-metallicity and more massive MS stars; this leads to larger core masses and different evolutionary lifetimes for the merger systems. Thus, more ONeMg WD binaries can be formed at lower metallicity and for a higher total mass. There are few or no WD CE merger systems with massive star companions (especially with a combined mass  $> 15M_{\odot}$ ) in models 4 and 5, in comparison to the other models, because more massive star systems can survive or avoid the CE phase for the adopted  $\lambda$  and mass-transfer prescriptions in model 4 and 5 (Table 1 and Figure 3) for the same reasons as discussed above.

Now consider ONeMg WD CE events in which the companion star is a non-degenerate He star. The ONeMg WD + He star CE event channel is realized for the following ranges in the initial binary parameters: initial primary mass,  $M_{1,i} \sim 6.34 - 9.1M_{\odot}$ , secondary initial mass  $M_{2,i} \sim 2.1 - 7.9M_{\odot}$  and initial orbital period  $P_{\text{orb},i} \sim 0.03 - 40.0$  d. The mass range of the ONeMg WDs in this channel lies between  $\sim 1.07$  and  $\sim 1.42M_{\odot}$  while the He stars' mass is mainly distributed between  $\sim 0.75$  and  $\sim 1.5M_{\odot}$  (up to  $\sim 2.25M_{\odot}$ ; see Figure 4). The rates ( $0.34 - 10.78 \times 10^{-5}M_{\odot}^{-1}$ ) in Table 2 show that at most  $\sim 10\%$  of all CE events of CO WDs + He stars end up with mergers for the condition  $M_{\text{com}} \geq 1.44M_{\odot}$ . The evolutionary delay times lie between  $\sim 0.05$  and 1.0 Gyr. The different patches in Figure 4 are caused by different evolutionary routes to form WD + He star binaries. Figure 4 shows that the mass distributions for

the cores and envelopes of He stars for the standard model 1 have a relatively narrow range between  $\sim 0.3$  and  $\sim 1.0M_{\odot}$ . The lower rates and narrow mass ranges suggest that ONeMg WDs that merge with the core of a He star companion may not play as important a role as mergers with different types of companions. However, this might be the origin for some rare transients and objects where no hydrogen lines are detected. Our result suggests that this channel could produce millisecond pulsars as well as magnetars. Moriya et al. (2018b) studied the fallback accretion central engine model for hydrogen-poor SLSNe; they showed that  $\geq 2M_{\odot}$  needs to be accreted for powering SLSNe by fallback accretion. The derived envelope masses in Figure 4 are smaller than the minimum value suggested by Moriya et al. (2018b; Nicholl et al. 2017); therefore it is not clear whether the central objects formed in this channel may be able to produce fallback accretion powered type I SLSNe.

### 3.2 Possible BH Formation through CMIC inside the CE

Stellar evolution models suggest that stellar mass BHs are the final products of massive stars  $\geq 20 - 25 M_{\odot}$  (e.g., Woosley & Weaver 1995). Recent numerical simulations (e.g., O'Connor & Ott 2011; Ugliano et al. 2012; Sukhbold & Woosley 2014; Pejcha & Thompson 2015; Ertl et al. 2016; Sukhbold et al. 2016; Schneider et al. 2021) indicate that the outcome of neutrino-driven explosions is largely controlled by the final core structure of massive stars, and a clear mass limit for a progenitor star to end its evolution as a BH is hard to establish. The likelihood of a successful explosion or of BH formation is related to the compactness of the stellar core (e.g., O'Connor & Ott 2011; Sukhbold et al. 2016; Raithel et al. 2018). Observational and theoretical results suggest different progenitor mass ranges for failed SNe and BH formation (Smartt 2009, 2015; Kochanek 2014; Schneider et al. 2021). Sukhbold et al. (2016) suggested that single zero-age MS stars with masses as low as  $15M_{\odot}$  could produce BHs, while Schneider et al. (2021) showed that, for stripped stars in binaries, a much higher initial mass is likely to be required. On the other hand, in binary systems there are other ways, e.g., stellar mergers (Wiktorowicz et al. 2019) that could produce BHs. Here, we propose the CMIC scenario as an additional channel for producing BHs which is the final outcome of the merger of an ONeMg WD and the core of its companion during the CE phase. Here we assume that a BH is formed when the total mass of the system is larger than  $15M_{\odot}$  if the merger occurs in a CE. The newborn BH formed through CMIC may be surrounded by an accretion disc formed by the ejected material as shown in the typical example illustrated in Figure 5. Note that the core of the merger system with the whole mass of  $15M_{\odot}$  in our model is already an ONeMg WD, thus the core density is significantly higher than that of a normal MS star with the same mass studied in Sukhbold et al. (2016). In this merger process, there may be a quick transition from a NS to a BH (e.g., Moriya et al. 2016) due to the heavy core and the large amount of fallback material after the collapse of the heavy ONeMg WD (in Figure 5, we only show the final possible outcome).

The results of our calculations in Figure 2 show that the initial mass for the primaries can be as high as  $\sim 11 M_{\odot}$ . For the mergers, the secondary mass, secondary core mass, secondary envelope mass can be as high as  $\sim 21M_{\odot}$ ,  $\sim 6.5M_{\odot}$  and  $\sim 17M_{\odot}$ , respectively. The ONeMg WDs tend to be more massive ( $> 1.2M_{\odot}$ ). The mass distributions are mainly affected by the metallicity, details of mass transfer and CE evolution (i.e., Figure 3; see the earlier discussion). The rate for BH formation in the CMIC channel is as high as  $3.48 \times 10^{-5} M_{\odot}^{-1}$  (Table 2). This implies that this channel makes a contribution of at least a few percent to the BH population. The

massive CE would not be ejected far away during the CMIC and fast NS to BH transition process, and at least some fraction of the ejected material in a core collapse supernova explosion may remain bound to the compact remnant. Thus, the BH formed in this way may be surrounded by an accretion disk due to the turn-around and fallback as shown in the example in Figure 5. The accretion power released when material falls back onto the compact remnant at late times could power unusual SNe such as superluminous or otherwise peculiar supernovae (e.g., Dexter & Kasen 2013). Therefore, the BH formed in this proposed formation channel could potentially power type II SLSNe.

## 4 DISCUSSION

*Rates/Contributions:* Adopting a star formation rate of  $2 M_{\odot} \text{ yr}^{-1}$  and binary fraction of 0.7, we can estimate the Galactic rates of peculiar objects and transients formed via the CMIC scenario as follow (the two values given below refer to the standard model and our model 4, respectively): (1) MSPs/Pulsars have rates of  $8.81 \times 10^{-5} \text{ yr}^{-1}$  and  $6.57 \times 10^{-5} \text{ yr}^{-1}$ . These pulsars can be the explanation for the retention of NSs in globular clusters. (2) The rate of TZO, including the possibility of Type II CCSNe/SLSNe and BHs powered by AIC of the cores, are  $1.36 \times 10^{-4} \text{ yr}^{-1}$  and  $5.76 \times 10^{-5} \text{ yr}^{-1}$ . (3) Magnetars and SLSNe powered by these magnetars have rates of  $3.36 \times 10^{-5} \text{ yr}^{-1}$  and  $1.95 \times 10^{-5} \text{ yr}^{-1}$ . (4) BHs and possible SLSNe have rates of  $3.23 \times 10^{-5} \text{ yr}^{-1}$  and  $0.11 \times 10^{-5} \text{ yr}^{-1}$ . Contributions of three objects (TZO, magnetar and BH) to produce SLSNe lie between  $7.82 \times 10^{-5} \text{ yr}^{-1}$  and  $\sim 2 \times 10^{-4} \text{ yr}^{-1}$ . If we combine the rates for BHs formed right after CMIC and formed through AIC of core NSs in TZOs, the Galactic rates of BHs range from  $5.87 \times 10^{-5} \text{ yr}^{-1}$  to  $1.68 \times 10^{-4} \text{ yr}^{-1}$ ; this means that these BH formation pathways make a non-negligible contribution to the overall BH population.

Up to April 2014, according to the ATNF Pulsar Catalogue (Manchester et al. 2005), 2016 pulsars with measured values of spin period and its time derivative had been discovered. Among these, 1847 were single pulsars, a few percent millisecond pulsars, 55 of them in SN remnants, and 29 single magnetars. Based on the CMIC model results, about 1000 – 6500 pulsars can be formed, a large fraction of which are likely to be millisecond pulsars, and about 30-100 could be magnetars (if we take the observed fraction of magnetized WDs into consideration for CMIC; Note that here it should be combined rates of all three channels of CMIC). Thus, those observed numbers given above can be reproduced by the CMIC channel proposed in this work. However, it is worth noting that the consistency between our rates and observational results only shows the importance of the formation scenarios in this work, and it does not mean that other possible formation ways could be excluded. Most interestingly, previous studies show the importance of the immediate surroundings of a magnetar for fast radio bursts (FRBs) production in relativistic shock wave models (e.g., Khangulyan et al. 2021). Magnetars formed through CMIC in this work can be immediately surrounded by envelope matters, thus the newborn magnetars in this work may produce FRBs. Compared to the NS population, the CMIC channel makes a small contribution to the BH population. Because the rate of type II SLSNe is not observationally well-determined yet, we roughly take the rate of type II SLSNe as  $\sim 10^{-5} \text{ yr}^{-1}$  according to Quimby et al. (2013). Considering all cases of NS/BH central engine models in our study, the predicted rates range from  $\sim 10^{-5} \text{ yr}^{-1}$  up to  $\sim 2 \times 10^{-4} \text{ yr}^{-1}$ . Table 4 shows general rates of SLSNe which might be originated from mergers in different types of WD binaries. For rates of various transients and different objects formed through

the stellar-core mergers from WD binaries, see Ablimit (2021) and this paper. From the table, it can be seen that different assumptions (especially different models for the CE evolution and mass transfer) could change the rate by more than an order of magnitude, and it again shows the important role of CE evolution, mass transfer and metallicity (see above sections for more discussions). Derived rates in the merger scenarios are compatible with the observational estimate, although both of these estimates are inherently uncertain (see below for other limitations).

*Related further evolution:* Above we investigated only mergers inside a CE. But what about the systems that survive from the CE as WD binaries? WD binaries are the one kind of X-ray binaries, and these X-ray binaries have the connection to GW sources (e.g., Abdusalam et al. 2020). One particularly interesting final outcome of a ONeMg WD with a massive star companion evolved from the CE is a WD-NS binary or possibly a WD-BH system with a sufficiently close orbit to merge within a Hubble time. These WD-NS and WD-BH binaries are excellent GW sources and may create peculiar transients (Portegies Zwart & Yungelson 1999; Paschalidis et al. 2004; Sabach & Soker 2014; Margalit & Metzger 2016; Toonen et al. 2018; Abdusalam et al. 2020; Bobrick et al. 2021), potentially observable with current and future transient surveys such as LISA. Because the formation of close WD-BH system is very model-dependent, there is no such system with the rapid remnant-mass model of Fryer et al. (2012), and ONeMg WD- NS systems are the final outcomes survived from the CE evolution of ONeMg WD-massive star binaries in this study. After CE ejection, the two stars move closer towards each other due to various angular-momentum loss mechanisms (i.e. GW radiation), and the resulting close ONeMg WD-NS systems will merge within the Hubble time if they are sufficiently close after the CE phase. Table 3 shows the rates of these ONeMg WD-NS binaries for the different models, where the rate could be as high as  $4.95 \times 10^{-5} M_{\odot}^{-1}$ . The rather non-conservative mass-transfer model adopted in this work makes more primordial binaries have stable mass transfer, reducing the number of CE events. With the potentially more reliable treatment of  $\lambda$  in model 4, more binaries can successfully survive from the CE phase if they evolve into a CE phase in the first place. Considering the formation of WD-NS systems and the contribution of mergers to these peculiar objects, our model 4 is the most favorable one compared to the other models.

*Limitations/Uncertainties:* It is worth to raise that the critical total mass of the WD core merged system to form a BH or a NS is very uncertain (it might be lower or higher than the adopted value ( $15M_{\odot}$ ) in this work), we just adopted a possible value according to the previous work as discussed above, and this needs further investigations. The central NS objects (e.g., pulsars and TZO etc.) formed through CMIC could eventually become BHs if they accrete enough mass from fallback/surrounded materials to exceed the maximum NS mass. One of the other biggest uncertainties in this work is the detailed nature of newborn NSs formed through CMIC; we have discussed various possibilities, but this clearly needs further investigation. Besides, there are many physical processes and parameters in the binary evolution pathways which still remain uncertain, specifically the CE phase, the existence of accretion discs around the collapsed object, and the physical response at very high mass-transfer rates. It is relatively easy to simulate all these parameters in BPS simulations, i.e. the initial conditions, prescriptions for stable/unstable mass transfer, treatments of common envelope (CE) evolution etc. The numbers of binaries, special objects and merger systems are affected strongly by the treatment of all these physical processes and parameters, most of all by the parameters for the CE phase and the nature of the mass transfer. In our BPS simulations we

used a range of acceptable/common ways by considering new evolutionary models. Future more detailed theoretical and observational studies should provide more information and constraints to improve our understanding.

## 5 CONCLUSION

We have proposed several possible new evolutionary pathways to form (millisecond) pulsars, Thorne-Żytkow objects, magnetars and BHs, through core merger-induced collapse during the CE phase of ONeMg WD binaries with hydrogen-rich intermediate-mass/massive stars and stripped helium-rich stars. We have systematically investigated the CMIC model from ONeMg binaries as origin for those objects, and discussed possibilities of powering two types of SLSNe and FRBs etc. By comparing our simulations with observationally inferred values of known peculiar NS objects, BH population and estimates of the SLSN rate, we conclude that the CMIC scenario can make a significant contribution to those peculiar transients and objects. We expect that future observations with more information including robust estimates of the number/rate of these systems and transients will be useful for further testing the scenario proposed in this work.

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## DATA AVAILABILITY:

The data underlying this article will be shared on reasonable request to the corresponding author.

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**Table 1.** Meanings of abbreviations used in the text and figures.

Abbreviation	Meaning
AGB	Asymptotic giant branch (star)
AIC	Accretion-induced collapse
BH	Black hole
BPS	Binary population synthesis
CCSN(e)	Core-collapse supernova(e)
CE	Common envelope
CHeB	Core helium burning (star)
CMIC	Core merger-induced collapse
CO	Carbon/oxygen
ECSN(e)	Electron-capture supernova(e)
GW	Gravitational wave
HeMS	Star on the equivalent of the main sequence for hydrogen-poor helium-burning stars
HeG	Hydrogen-poor helium-burning giant
HG	Hertzsprung-gap (star)
k1	Type of the primary star in a binary
k2	Type of the secondary star in a binary
MIC	merger-induced collapse
MS	Main sequence
MSP	Millisecond pulsar
NS	Neutron star
ONeMg	Oxygen/neon/magnesium
SN(e)	Supernova(e)
SLSNe	Superluminous Supernovae
TZO	Thorne-Żytkow object
WD	White dwarf

**Table 2.** Different models in our calculation

Model	$\alpha_{\text{CE}}$	$\lambda$	$q_{\text{c}}$	$Z$
mod1	1.0	0.5	$q_{\text{const}}$	0.02
mod2	0.1	0.5	$q_{\text{const}}$	0.02
mod3	1.0	0.5	$q_{\text{const}}$	0.001
mod4	1.0	$\lambda_{\text{w}}$	$q_{\text{const}}$	0.02
mod5	1.0	$\lambda_{\text{w}}$	$q_{\text{cs}}$	0.02

**Table 3.** Calculated rates ( $R$ ) of ONeMg WD/non-degenerate star CE events for five different models (in  $10^{-5} M_{\odot}^{-1}$ )

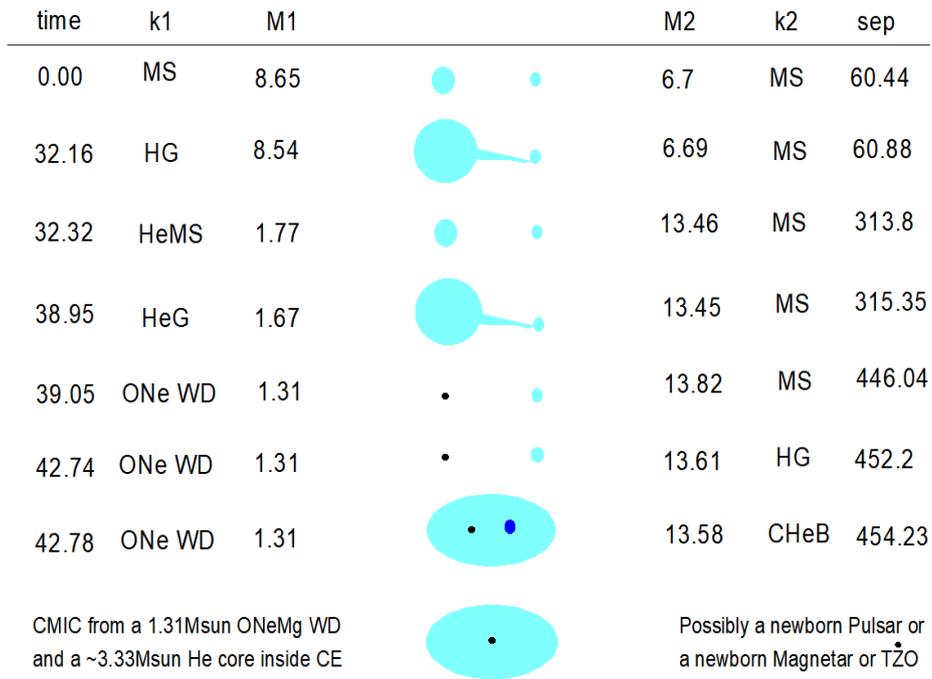
CE events of ONeMg WDs/companion stars	$R1$	$R2$	$R3$	$R4$	$R5$
ONeMg WDs/normal stars (all CE)	33.04	15.43	41.34	33.94	15.94
ONeMg WDs/normal stars (all merger)	18.51	12.03	19.90	9.62	0.52
ONeMg WDs/normal stars (merger con1)	6.29	4.96	7.38	4.69	0.24
ONeMg WDs/normal stars (merger con2)	9.75	4.57	9.04	4.12	0.00
ONeMg WDs/normal stars (merger con3)	2.31	2.32	3.48	0.08	0.00
ONeMg WDs/He stars (all CE)	2.31	0.34	3.78	10.78	10.62
ONeMg WDs/He stars (Merger with $M_{\text{com}} \geq 1.44M_{\odot}$ )	0.56	0.26	0.36	1.06	0.47
ONeMg WDs - neutron star systems (experienced CE)	0.11	0.0	0.06	4.27	4.95

Note: Rates in the table are calculated with  $R = \frac{\text{Event numbers}}{\text{Total mass} (\sim 10^7 M_{\odot} \text{ in this work}) \text{ yielded in a simulation run}}$ . Normal stars mean sub-giant or giant branch stars with hydrogen-rich envelopes; He-rich stars are (sub)giant helium stars, and all mergers with He stars have combined core masses of  $M_{\text{com}} \geq 1.44$ . Merger con1 means that the combined mass of the core and the secondary is  $M_{\text{com}} \geq 1.44M_{\odot}$  and the whole mass  $M_{\text{all}} < 8.0M_{\odot}$ , merger con2 means that  $M_{\text{com}} \geq 1.44M_{\odot}$  and  $8.0 \leq M_{\text{all}} < 15.0M_{\odot}$ , and merger con3 that  $M_{\text{com}} \geq 1.44M_{\odot}$  and  $M_{\text{all}} \geq 15.0M_{\odot}$  during the CE phase. Event numbers can easily be calculated by multiplying the numbers in the table by  $R \times 10^7$ , and the birthrate can be determined by choosing a star formation rate in  $M_{\odot} \text{ yr}^{-1}$  ( $SFR$ ) and binary fraction ( $f_{\text{bin}}$ ) and multiplying the numbers in the table by  $SFR \times f_{\text{bin}} \times R$ .

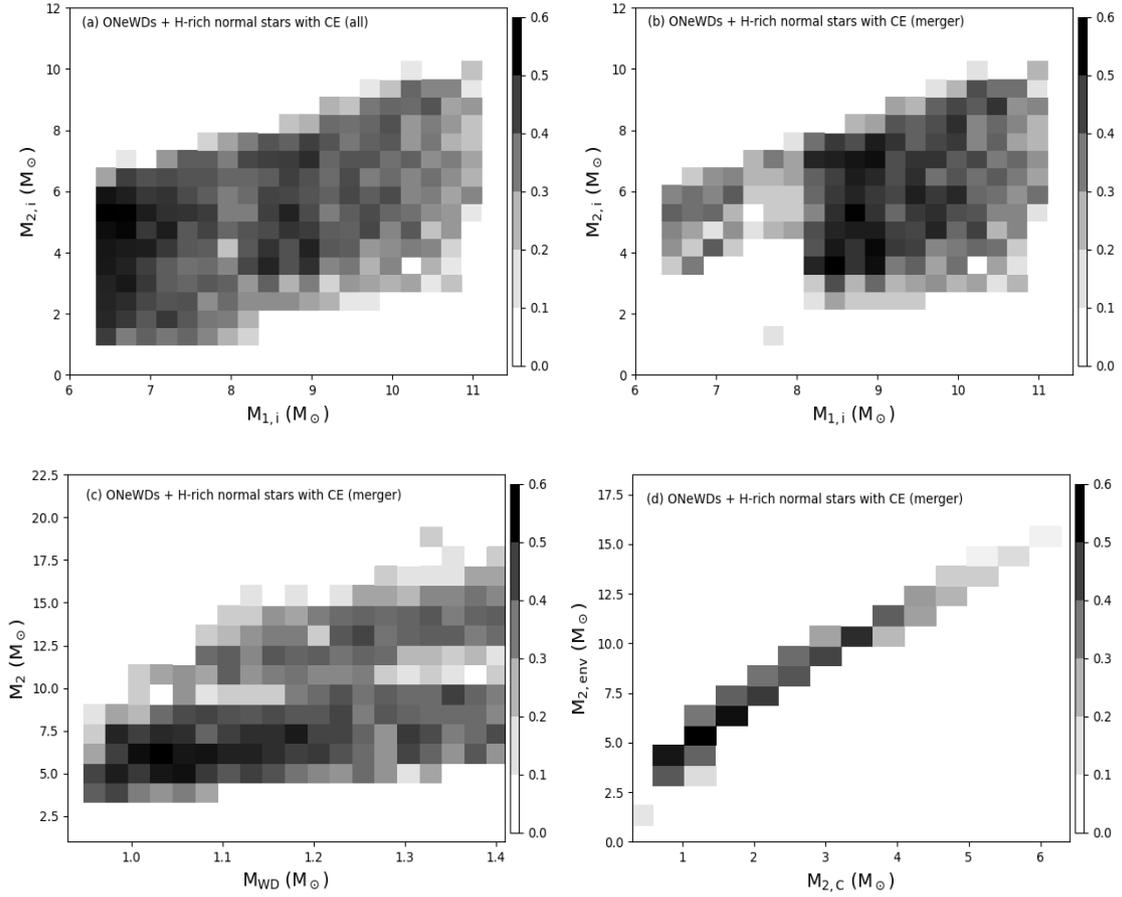
**Table 4.** Galactic birthrates ( $R_B$ ) of stellar core-mergers which may produce SLSNe: a comparison between mergers of CO WD/massive star CE events ( $R_{B,S-CO}$ ) and mergers of ONeMg WD/normal star CE events with two massive cases ( $R_{B,S-ONe}$ ) for five different models (in  $10^{-5} \text{ yr}^{-1}$ )

Model	$R_{B,S-CO}$ ( $M_{WD} \geq 0.9M_{\odot}$ )	$R_{B,S-ONe}$ ( $8.0 \leq M_{all} < 15.0M_{\odot}$ )	$R_{B,S-ONe}$ ( $M_{all} \geq 15.0M_{\odot}$ )
mod1	10.10	19.50	4.62
mod2	24.36	9.14	4.64
mod3	17.88	18.08	6.96
mod4	7.08	8.24	0.16
mod5	1.70	0.0	0.0

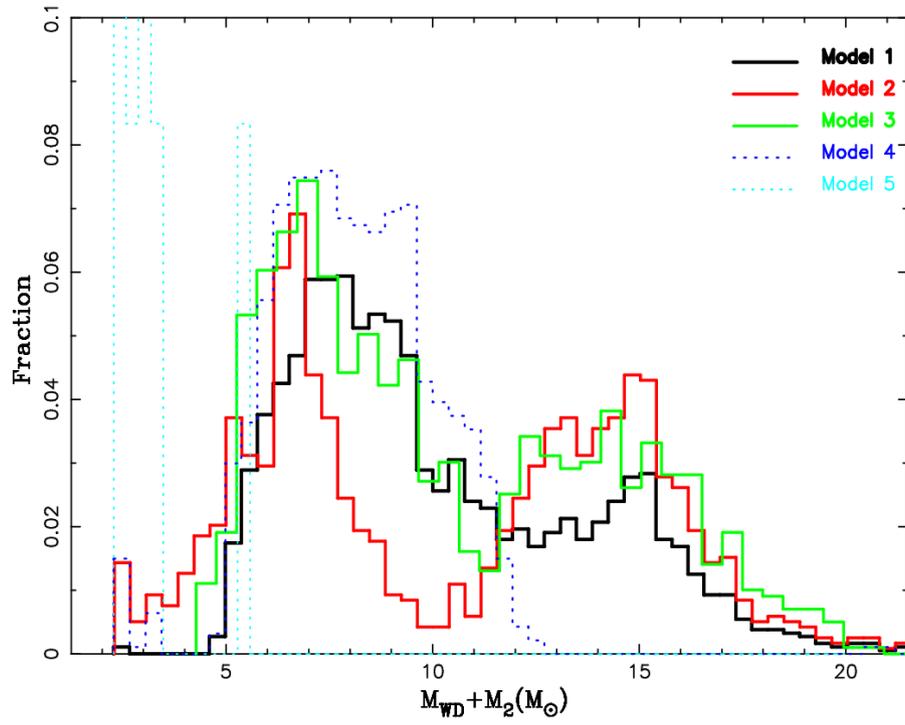
Note: This table only shows the Galactic rates (adopting SFR as  $2 M_{\odot} \text{ yr}^{-1}$ ) of SLSNe originated from mergers of between CO WDs ( $M_{WD} \geq 0.9M_{\odot}$ ) and cores of massive stars ( $M_2 \geq 8.0M_{\odot}$ ) inside the CE, and from massive merger products ( $M_{all} \geq 8.0M_{\odot}$ ) of ONeMg WDs and non-degenerate hydrogen-rich stars CE events. This table does not include other possibilities like SLSNe triggered by mergers of between CO WDs ( $M_{WD} \geq 1.0M_{\odot}$ ) and cores of massive stars or mergers between WDs and cores of less massive ones ( $< 8.0M_{\odot}$ ) or mergers of between WDs and cores of stripped He stars. For other transients like CMIC or SNe Ia or other possibilities for SLSNe, other tables including discussions in this work and Ablimit (2021) can be used, and different SFR can be adopted with rates of those tables in this work and Ablimit (2021) to calculate the Galactic rates for a real comparison with future works.



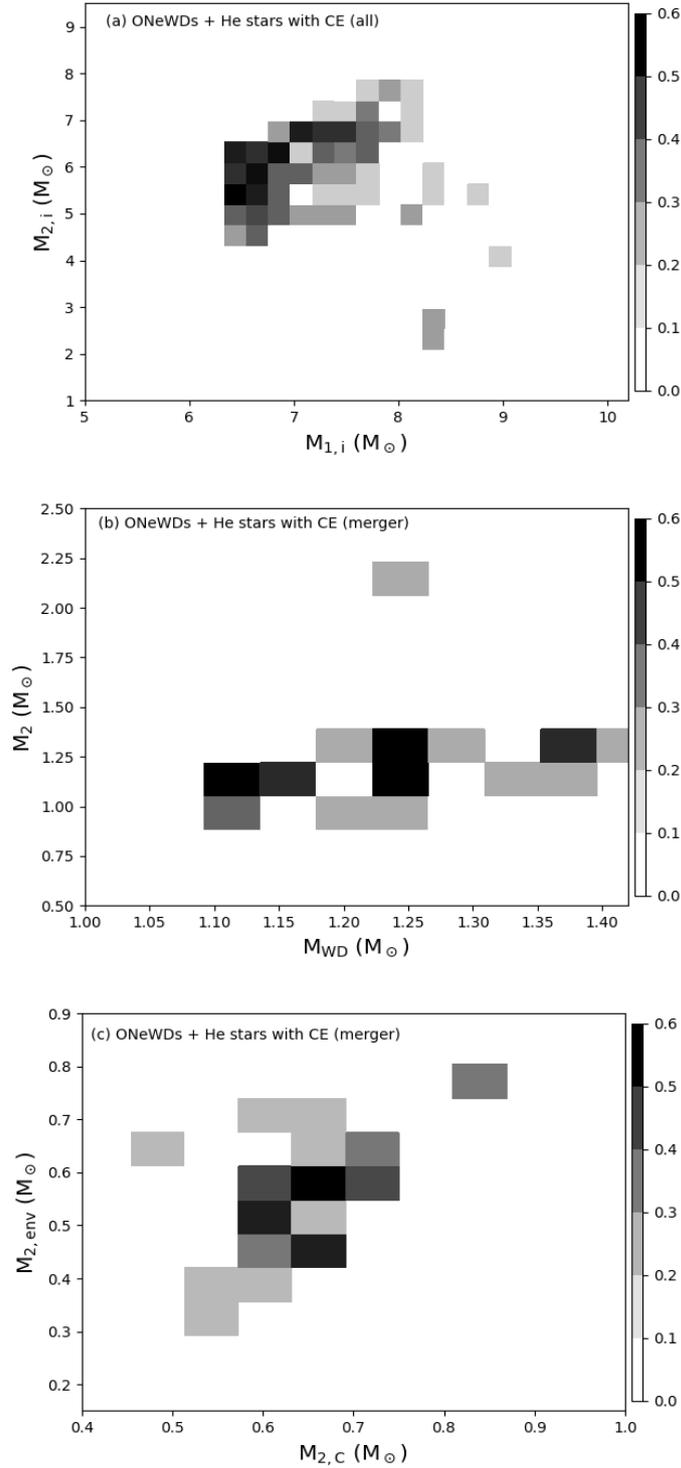
**Figure 1.** Example of the evolution of a system to the channel for the merger between a ONeMg WD and He core of a massive star based on model 1. The primary (mass is M1) experiences two phases of mass transfer before forming the ONeMg WD. Afterwards, the secondary (mass is M2) fills its Roche lobe at the core helium burning stage of the evolution (CHeB), and its envelope engulfs the ONeMg WD and its core due to the unstable mass transfer. The abbreviations of the stellar types (k1 is the type of the primary star, and k2 is type of the secondary star in a binary) are defined in the text. The evolution time is in Myr, and separation (sep) between two stars is in  $R_{\odot}$ .



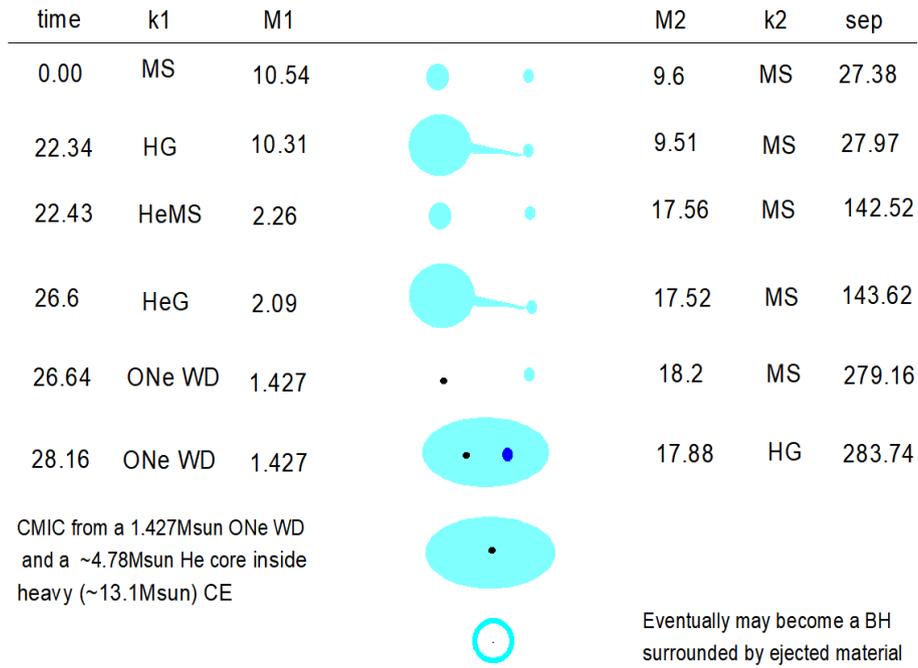
**Figure 2.** The normalized/weighted number density distributions from simulated results of model 1 (standard model). (a) and (b) show the initial mass relation of primary MS ( $M_{1,i}$ ) and secondary MS stars ( $M_{2,i}$ ) in primordial binaries which form all ONeMg WD + normal star binaries with CE (upper left), and ONeMg WD + normal star systems which experience the CE and leading to core mergers (upper right), respectively. Mass relations at the beginning of the CE between the ONeMg WD and its companion star for ONeMg WD + normal star systems, and secondaries' core and envelope mass relations for the merger case under the condition of  $M_{WD} + M_{2,C} \geq 1.44$  are given in (c) and (d), respectively.



**Figure 3.** The total mass distributions of merger systems between the ONeMg WDs and cores of the normal stars under the condition of  $M_{\text{WD}} + M_{2,C} \geq 1.44$  for five different models.



**Figure 4.** The normalized/weighted number density distributions from simulated results of model 1 (standard model) for the merger case of the ONeMg WD and core of the He stars under the condition of  $M_{WD} + M_{2,C} \geq 1.44$  at the onset of CE. (a) demonstrates the initial mass relation of primary MS ( $M_{1,i}$ ) and secondary MS stars ( $M_{2,i}$ ) in primordial binaries which form all ONeMg WD + He star binaries with CE. (b) shows the mass relation of the ONeMg WD ( $M_{WD}$ ) and secondary He stars ( $M_{He}$ ). Mass relations between the ONeMg WD and core of the He star for the merger case are given in (c).



**Figure 5.** Example of the merger between a ONeMg WD and He core of a massive star inside the CE based on model 1. The evolution is very similar to that of Fig. 1, and the main difference compared to the first example is that the combined core and total mass are higher, the CE event happens when the secondary becomes the HG star, and the evolution time is longer due to the different initial conditions. The column headings and units are same as that of Fig. 1.