Do SN 2002cx-like and SN Ia-CSM Objects Share the Same Origin?

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Abstract

SN 2002cx-like and SN Ia-CSM objects show similar early spectra and both belong to a young stellar population, suggesting that they could share the same progenitor origin. Adopting the framework of the common-envelope-wind model developed in Meng & Podsiadlowski, we propose that both subclasses of SNe Ia are caused by the explosion of hybrid carbon–oxygen–neon white dwarfs (CONe WDs) in single-degenerate systems, where SNe Ia-CSM explode in systems with a massive common envelope (CE) of \( \sim \)1.0, while SN 2002cx-like events correspond to those events where most of the CE has been lost in a wind. Using binary-population-synthesis calculations, we estimate a number ratio of SNe Ia-CSM to SN 2002cx-like objects between 1/3 and 2/3, consistent with observational constraints, and an overall contribution from hybrid CONe WDs to the total SN Ia population that also matches the observed number from these peculiar objects. Our model predicts a statistical sequence of circumstellar material density from SN Ia-CSM to SN 2002cx-like events and normal SNe Ia, consistent with existing radio constraints. We also find a new subclass of hybrid SNe that share the properties of Type II and Type Ia SNe, consistent with some observed SNe, which do not have a surviving companion. In some cases, these could even produce SNe Ia from apparently single WDs.

Key words: binaries: close – stars: evolution – supernovae: general – white dwarfs

1. Introduction

Although Type Ia supernovae (SNe Ia) are known to be astrophysical events of major importance, e.g., as standard candles to measure cosmological parameters (Riess et al. 1998; Perlmutter et al. 1999), the exact nature of their progenitors has remained unclear (Hillebrandt & Niemeyer 2000; Leibundgut 2000). There is a consensus that an SN Ia results from the thermonuclear explosion of a carbon/oxygen white dwarf (CO WD) in a binary system (Hoyle & Fowler 1960), but there is still a decade-long debate concerning the nature of the companion. Two basic scenarios for the progenitors of SNe Ia have been discussed for the last four decades. One is the single-degenerate (SD) model, where the CO WD accretes material from a nondegenerate companion star (Whelan & Iben 1973; Nomoto et al. 1984); the other is the double-degenerate model, involving the merger of two CO WDs (Iben & Tutukov 1984; Webink 1984). At present, support and counter-arguments exist for the two basic scenarios (Wang & Han 2012; Maoz et al. 2014) both on the observational and the theoretical side.

The detection of circumstellar material (CSM) in the spectrum of SNe Ia is usually taken as strong evidence in favor of the SD model for these objects (Dilday et al. 2012; Maguire et al. 2013). In particular, a new subclass of SN Ia-like objects shows the spectroscopic signatures of both SNe Ia and IIa in the form of broad Fe, Ca, S, and Si absorption lines with strong narrow Hα emission lines, which is explained by an SN Ia exploding in a dense CSM. The interaction between the supernova ejecta and the CSM partly contributes to their high luminosity. The first candidate for this subclass was SN 2002ic, which is characterized by the absorption features seen in SN 1991T-like SNe Ia and strong Hα emission lines (Hamuy et al. 2003). Such SNe Ia are referred to by various authors as SN Ia/IIa, Ia, IIa, Ia or SNe Ia-CSM (Silverman et al. 2013). Here, we denote such events as “SNe Ia-CSM” following Silverman et al. (2013). Although there is some debate regarding whether these objects are truly SNe Ia or in fact core-collapse (CC) SNe (Benetti et al. 2006; Inserra et al. 2014), the discovery of PTF11lx definitively shows that at least some of the SN Ia-CSM events are connected with SNe Ia (Dilday et al. 2012). In addition, the host galaxies of all SNe Ia-CSM are late-type spirals, which implies that these objects originate from a relatively young stellar population (Silverman et al. 2013). Within the common-envelope-wind (CEW) model, Meng & Podsiadlowski (2017) suggested that 2002ic-like SNe are connected with the explosion of CO WDs in a massive common envelope (CE), but this interpretation seems to have difficulty explaining the event rate for the whole SN Ia-CSM class.

SN 2002cx has been called the most peculiar known SN Ia (Li et al. 2002). Similarly to SN Ia-CSM objects, 2002cx-like SNe also exhibit SN 1991T-like pre-maximum spectra (Li et al. 2002). Moreover, just as SN Ia-CSM objects, 2002cx-like SNe favor late-type galaxies (Foley et al. 2013; Lyman et al. 2018). In addition, although radio observations provide only an upper limit on the CSM density, an analysis of the upper limit based on analytical models for the temporal and spectral evolution of prompt radio emission from the interaction with the CSM shows that, compared with normal SNe Ia, SN 2002cx-like events seem to have a relatively dense CSM, but not as dense as SNe Ia-CSM (e.g., Figure 7 in Chomiuk et al. 2016). Does the similarity between SN 2002cx-like and SN Ia-CSM objects imply that they share the same progenitor channel? Recently, 2002cx-like SNe were proposed to be caused by the explosions of hybrid carbon–oxygen–neon (CONe) WDs in SD systems (Meng & Podsiadlowski 2014; Wang et al. 2014); the chemical evolution of dwarf spheroidal galaxies may even provide some indirect support for this.
suggestion, i.e., if there were no contributions of subluminous SNe Ia from hybrid CONe WDs, the spread of [Mn/Fe] in dwarf spheroidal galaxies could not be reproduced (Kobayashi et al. 2015; Cescutti & Kobayashi 2017). Furthermore, numerical simulations have demonstrated that the explosions of hybrid CONe WDs could reproduce their properties, e.g., their low luminosity, low kinetic energy, and even their light curve and spectrum (Kromer et al. 2015; Bravo et al. 2016). If SN 2002cx-like and SNe Ia-CSM objects share the same origin, could the hybrid CONe WD channel simultaneously explain the origin of both types? In this paper, we investigate this question and show that they could in principle.

In Section 2, we briefly describe our method and present the results of our calculations in Section 3, followed with a detailed discussion of the results and conclusions in Section 4.

2. Method

Recently, Meng & Podsiadlowski (2017) constructed a new version of the SD model, in which a CE is assumed to form when the mass-transfer rate between a CO WD and its companion exceeds a critical accretion rate, rather than the onset of an optically thick wind (OTW; Hachisu et al. 1996). The WD can then gradually increase its mass at the base of the CE similarly to the degenerate core in a thermally pulsing asymptotic-giant-branch star. For the large nuclear luminosity from stable hydrogen burning, the CE will expand to giant dimensions and lose mass from the surface of the CE by a CE wind; this leads to a low CE density and a correspondingly low frictional luminosity between the binary system and the CE. As a result, the binary system will avoid a fast spiral-in phase for a large parameter range and eventually re-emerge from the CE phase, instead of merging completely. In the CEW model, the SN Ia may explode in the CE phase, in a phase of stable hydrogen burning (related to a supersoft X-ray source [SSS] phase) or a phase of weakly unstable hydrogen burning, where the system would appear as a recurrent nova [RN]. The CEW model shares many of the merits of the OTW model while avoiding some of its shortcomings.

In this paper, we calculate the evolution of potential SN Ia progenitor binaries following the method developed in Meng & Podsiadlowski (2017), except that the WDs are assumed to be hybrid CONe WDs. Hybrid CONe WDs could be as massive as 1.30 $M_\odot$, which means that WDs do not need to accrete much mass to reach the Chandrasekhar limit (Denissenkov et al. 2013; Chen et al. 2014). Here, we only consider the case where the companion is a main-sequence or a sub-giant star (WD + MS) since the contribution to the total SN Ia rate from WD binaries with red-giant (RG) companions is quite uncertain: it is not entirely clear whether a WD + RG system enters into a dynamically unstable CE or a thermal timescale CE as required by our CEW model (e.g., Yungelson et al. 1995; Hachisu et al. 1999; Han & Podsiadlowski 2004; Ge et al. 2015; Liu et al. 2017). Throughout this work, “CE” implies a thermal timescale CE, rather than a dynamically unstable CE, unless otherwise specified. All WD + MS systems in our study must have experienced a dynamically unstable CE before they were formed. We calculated a dense grid of models where we varied the initial WD masses, secondary masses, and orbital periods and assumed that an SN Ia occurs when $M_{WD} = 1.378 M_\odot$ (Nomoto et al. 1984). Similarly to what was found in Meng & Podsiadlowski (2017), SNe Ia may explode in CE, SSS, or RN phases, which is the key feature for trying to simultaneously explain the properties of SN 2002cx-like and SN Ia-CSM objects.

Here, we first summarize our proposed scheme on SN 2002cx-like and SN Ia-CSM objects in a schematic diagram in Figure 1. At the time when $M_{WD} = 1.378 M_\odot$, the CE mass around the WD, which provides the mass reservoir to form the CSM, tends to be bimodal, containing either $\geq 0.1 M_\odot$ of matter or less than a few $10^{-3} M_\odot$ (Figure 5). If the spin-down timescale were $\sim 10^6$ yr, the CSM near the central supernova at the time of the explosion would contain so little mass that it would be very difficult to directly detect a signal from the interaction between the supernova ejecta and the low-mass nearby CSM. However, for systems with massive CEs, the supernova ejecta will catch up with the dense CSM after several days (depending on the CE mass and wind velocity, see Section 4.2 for details). Such an interaction would show narrow hydrogen emission lines such as that seen in the spectra of SNe Ia-CSM. Otherwise, 2002cx-like SNe are expected if there is no dense CSM around the supernova. Moreover, some systems are expected to experience a delayed dynamical instability and merge soon after $M_{WD} = 1.378 M_\odot$; this predicts a new subclass of either hybrid SNe or SNe Ia from single WDs, where the hybrid objects show features of both SNe II and SNe Ia (such as suggested for SN 2012ca), but without a surviving companion (see Section 3.1 for details).

We then performed two binary-population-synthesis (BPS) simulations adopting this new model grid with the rapid binary evolution code developed by Hurley et al. (2000, 2002). Hurley et al.’s code does not include hybrid CONe WDs. Following Meng & Podsiadlowski (2014), we assumed that, if a WD is less massive than $1.3 M_\odot$ based on the results in Chen et al. (2014) and is not a CO WD, it is a hybrid CONe WD. If a binary system in the simulations evolves to the CONe WD + MS stage and the system is located in the $(\log P, M_{WD})$ plane for an SN Ia at the onset of Roche-lobe overflow (RLOF), we assume that an SN Ia occurs regardless of how massive the CO core is in the hybrid WD. We followed the evolution of 107 binaries, where the primordial binary samples are generated in a Monte Carlo way with the following input assumptions: (1) a constant star formation rate; (2) the initial mass function (IMF) of Miller & Scalo (1979); (3) a uniform mass-ratio distribution; (4) a uniform distribution of separations in log $a$ for binaries, where $a$ is the orbital separation; (5) circular orbits for all binaries; and (6) a CE ejection efficiency of $\alpha_{CE} = 1.0$ or $\alpha_{CE} = 3.0$, where $\alpha_{CE}$ denotes the fraction of the released orbital energy used to eject the CE (see Meng & Podsiadlowski 2017 for further details).

3. Results

Generally, the binary evolution sequences for CONe WD + MS systems are similar to those shown in Meng & Podsiadlowski (2017); i.e., mass transfer begins when the companion is an MS star or crosses the Hertzsprung gap. When $M_2$ exceeds a critical accretion rate, the system enters into the CE phase, and the hybrid CONe WD increases its mass at the base of the CE. When its mass reaches 1.378 $M_\odot$, an SN Ia is assumed to occur where the system can be in a CE, SSS, or RN phase.
3.1. An Example of a Delayed Dynamical Instability

However, for the case of $M_{\text{WD}} = 1.3 M_\odot$, the evolution of some of the systems differs from the canonical evolution in an interesting way, an example of which is shown in Figure 2. For the system in Figure 2, the initial companion is relatively massive and the initial orbital period is short. Due to the short initial orbital period, the donor star fills its Roche lobe on the MS, and the system enters into the CE phase soon thereafter. The WD increases its mass at the base of the CE, and, after $\sim 1.1 \times 10^5$ yr, the WD reaches $M_{\text{WD}} = 1.378 M_\odot$, where the CE still exists. Since rapidly rotating WDs may explode at a higher mass than $1.378 M_\odot$ (Yoon & Langer 2004, 2005), we continued our calculations beyond this mass, assuming the same WD growth pattern as for $M_{\text{WD}} < 1.378 M_\odot$. We found that after a few $10^7$ yr, the system will then experience a delayed dynamical instability, in which the initially stable mass transfer becomes dynamically unstable later, and then leads to a dynamically unstable CE (Hjellming & Webbink 1987).

For a rapidly rotating super-Chandrasekhar WD, it must experience a spin-down phase before it explodes as an SN Ia (Justham 2011; Di Stefano & Kilic 2012), but the spin-down timescale is quite uncertain (Di Stefano et al. 2011; Meng & Podsiadlowski 2013). For a nonaccreting WD, the spin-down timescale is very likely longer than $10^7$ yr, but less than a few $10^7$ yr (Di Stefano & Kilic 2012; Meng & Podsiadlowski 2013). So, if the delay time from the point when $M_{\text{WD}} = 1.378 M_\odot$ to the explosion is longer than the timescale for the delayed dynamical instability, the system in Figure 2 would merge before it explodes as an SN Ia, leaving the WD at the center of the CE and essentially forming a single AGB star with an overmassive core. If the core is spun down within its envelope and carbon is ignited at the center of the hybrid CONe core while there still is a massive envelope around it, the resulting supernova would have some very unusual properties (produce an SN I 1/2 in the nomenclature of Iben & Renzini 1983), with properties between those of a CC SN and an SN Ia, an example of which may be provided by SN 2012ca (Inserra et al. 2014, 2016). If the envelope is ejected before carbon is ignited in the center, it would lead to the thermonuclear explosion of an apparently single CONe WD. In either case, there would be no surviving companion left after the explosion.

3.2. Final Outcomes of the Binary Evolution Calculations

As shown in Meng & Podsiadlowski (2017), WDs may explode in a CE, SSS, or RN phase. When the WD explodes in a CE phase, the CE masses typically lie in the range of a few $10^{-4} M_\odot$ to a few $10^{-3} M_\odot$. It is difficult to detect this hydrogen-rich material directly. However, such low-mass CEs might leave footprints in the high-velocity features in the spectrum of SNe Ia (Mazzali et al. 2005a, 2005b). In a few cases, the CE mass can be larger than $0.1 M_\odot$, even as large as $0.1 M_\odot$. 

Figure 1. Schematic diagram illustrating the different channels for forming SN Ia-CSM, SN 2002cx-like, and hybrid/single SNe.
Such explosions may show the properties of 2002ic-like SNe. The results here are similar to those in Meng & Podsiadlowski (2017), except that the CE for some systems may be as massive as $2 M_\odot$. We show the results of our evolutionary calculations for $M_{\text{CE}} = 1.378 M_\odot$ as an example in Figure 3, where most of the systems will explode in the CE phase. Especially for the systems in the upper-right region, the CE mass is generally larger than $0.1 M_\odot$ when $M_{\text{WD}} = 1.378 M_\odot$.

In Figure 4, we show the contours leading to SNe Ia for different initial WD masses. In the figure, the triple-dotted-dashed line approximately marks the boundary between $M_{\text{CE}} \geq 0.1 M_\odot$ and $M_{\text{CE}} < 0.1 M_\odot$ when $M_{\text{WD}} = 1.378 M_\odot$. This clearly shows that a massive WD with $M_{\text{WD}} \geq 1.1 M_\odot$ is required for the system to explode with a massive CE. Moreover, only when the initial WDs are massive enough, i.e., $M_{\text{WD}} = 1.3 M_\odot$, may the explosions show hybrid properties of both CC SNe and SNe Ia.

### 3.3. The Distribution of $M_{\text{CE}}$

Since most hybrid CONe WDs will explode in the CE phase, we performed two BPS simulations with different values of the CE ejection parameter $\alpha_{\text{CE}}$ to obtain the CE mass distribution when $M_{\text{WD}} = 1.378 M_\odot$ (Figure 5). In Figure 5, the distribution of CE masses shows two peaks for either case, i.e., one around $\sim 1 M_\odot$ and one around $\sim 10^{-3} M_\odot$. The peaks can be explained by the different evolutionary stages and differences in mass-transfer rates at the onset of RLOF (see the detailed explanation in Meng & Podsiadlowski 2017). It may be difficult to detect a CE of $\sim 10^{-3} M_\odot$ directly, but the CE as massive as $\sim 1 M_\odot$ will be directly detectable as shown in the spectra of some SNe Ia-CSM (Silverman et al. 2013). Among all the SNe Ia with hybrid CONe WDs, about 25%–40% SNe Ia explode in massive CEs (note that Figure 5 only includes systems exploding in a CE phase, not those in SSS or RN phases). Because of the high initial WD masses, SNe Ia from hybrid CONe WDs originate from a relatively young population, i.e., with ages less than 1 Gyr (see also Meng & Podsiadlowski 2014).

As discussed above, hybrid CONe WDs may explode in different environments, i.e., in a CE phase with envelopes of different masses, an SSS phase, or an RN phase, leading to differences in the supernova properties. Considering that both SN 2002cx-like and SN Ia-CSM events show SN 1991T-like
spectra and are hosted in late-type galaxies and that numerical simulations of the explosions of hybrid CONe WDs can reproduce the properties of 2002cx-like SNe (Li et al. 2002; Silverman et al. 2013; Kromer et al. 2015), we propose that both subclasses originate from the explosion of hybrid CONe WDs in SD systems, where those exploding with massive CEs are associated with SN Ia-CSM events, while those exploding in less massive CEs or in an SSS/RN phase correspond to SN 2002cx-like SNe. In other words, SNe Ia-CSM have a denser CSM than 2002cx-like SNe. In addition, since most SNe Ia involving CO WDs explode in SSS/RN phases (Meng & Podsiadlowski 2017), our CEW model predicts that both SN Ia-CSM and SN 2002cx-like events statistically have a denser CSM than normal SNe Ia. At present, no such CSM density sequence has been reported observationally, but based on the analysis of an SN Ia sample without radio detections, an upper-limit sequence on the CSM density indeed exists around SN Ia-CSM, 2002cx-like SNe, and normal SNe Ia (Chomiuk et al. 2016). Future X-ray observations could provide more meaningful constraints on such a density sequence since X-ray observations are more sensitive than radio observations for CSM detections (Margutti et al. 2012, 2014; Meng & Han 2016).

Specifically, some SN Ia-CSM events could originate from the explosions of single stars as suggested in Section 3.1, and show the hybrid properties of CC SNe and SNe Ia as seen, e.g., in SN 2012ca (Inserra et al. 2014, 2016); however, such objects must be very rare for higher initial WD and companion masses according to the IMF of stars (Miller & Scalo 1979). In fact, in our BPS simulations with 10^7 binaries, no such object was produced: this would imply that such objects contribute less than ~0.03% to all SNe Ia. All binary systems in our study must have experienced a dynamically unstable CE and spiral-in phase in the past to form a WD + MS system. After the CE phase, binary systems with relatively massive WDs and companions tend to have relatively long orbital periods and produce SNe Ia exploding in massive CEs, i.e., they are SN Ia-CSM objects, rather than hybrid supernovae.

Here, we do not show the evolution of the SN Ia birth rate with time, since the evolution is very similar to that shown in Meng & Podsiadlowski (2014). However, because the parameter space leading to SNe Ia from the CEW model is larger than that from the OTW model, the birth rate from the CEW model is generally higher than that from the OTW model by ~30% (Meng & Podsiadlowski 2017). Similarly, the birth rate here is also higher than that in Meng & Podsiadlowski (2014) by roughly 10%–27%, depending on the adopted value for \( \alpha_{CE} \). Considering the various uncertainties discussed in Meng & Podsiadlowski (2014), we obtain a conservative upper limit for the contribution to all SNe Ia from hybrid CONe WDs of the order of 10% (as estimated by Meng & Podsiadlowski 2014). In addition, comparing this study with the results for CO WD + MS systems in Meng & Podsiadlowski (2017), we can estimate...
the number ratio of peculiar SNe Ia from hybrid CONe WDs to normal ones from CO WDs to be between 1/5 and 1/9, depending on the $\alpha_{\text{CE}}$ value. As expected, this ratio is probably larger than compatible with observations, e.g., 1/14 in Li et al. (2011) and 1/5–1/47 in Graur et al. (2017), since only CO WD + MS systems are considered to produce normal SNe Ia here.

## 4. Discussions and Conclusions

### 4.1. The Contribution of SNe Ia from Hybrid CONe WDs to All SNe Ia

In this paper, we have pointed out that SN 2002cx-like and SN Ia-CSM objects share two common properties, i.e., both subclasses of supernovae show an SN 1991T-like early spectrum and are hosted by late-type galaxies, and argued that they could share the same progenitor origin. Considering that the simulated explosions of hybrid CONe WDs appear to explain the properties of 2002cx-like SNe (see the discussions in Meng & Podsiadlowski 2014; Kromer et al. 2015; Bravo et al. 2016), we propose that both SN 2002cx-like and SN Ia-CSM objects originate from the explosions of hybrid CONe WDs in SD systems, based on the CEW model of Meng & Podsiadlowski (2017). The BPS calculations show that, depending on the value of $\alpha_{\text{CE}}$, roughly 25%–40% of SNe Ia with hybrid CONe WDs will show the properties of SN Ia-CSM objects. Hence, the predicted number ratio of SNe Ia-CSM to SN 2002cx-like objects is in the range of 1/3 to 2/3.

Foley et al. (2013) and Silverman et al. (2013) summarized the samples of SN 2002cx-like and SN Ia-CSM objects before 2013, respectively. In their samples, there are 25 SN 2002cx-like and 16 SN Ia-CSM objects. Hence, the observed number ratio of SNe Ia-CSM to SN 2002cx-like objects is 0.64 ± 0.18, where the error bars assumed a binomial distribution (Cameron 2011). Since some SNe IIn could be misclassified as SNe Ia-CSM (Benetti et al. 2006; Inserra et al. 2014) and SN Ia-CSM objects are generally brighter than 2002cx-like SNe, making them more easy to discover, the observed number ratio is likely an overestimate. Therefore, our predicted and the observed number ratios appear consistent with each other, at least within the observational errors. On the other hand, since the explosions of hybrid CONe WDs display significant variability, e.g., the range of $^{56}$Ni yields from hybrid CONe WDs is much wider than that from CO WDs (Kromer et al. 2015; Willcox et al. 2016), the properties of SN 2002cx-like and SN Ia-CSM objects would also appear more heterogeneous than normal SNe Ia, consistent with the diversity of observed 2002cx-like SNe (Foley et al. 2013).

The contribution of SNe Ia with hybrid CONe WD of all types is likely less than ~10% of the total SN Ia rate. Although estimates for the fraction of 2002cx-like SNe have varied significantly from ~5% to ~30% (Li et al. 2011; Foley et al. 2013), recent analyses based on volume-limited samples appear to favor a lower value around 5% (see, e.g., White et al. 2015; Ashall et al. 2016; Graur et al. 2017). One possibility for the large uncertainty of the contribution of 2002cx-like SNe is that the subclass of 2002cx-like SNe has a different origin since the subclass presents quite significant heterogeneity, e.g., their peak absolute magnitude ranges from $M_V \sim -14$ to $M_V \sim -19$, which is much larger than for other SNe Ia. Conceivably, the faint subclass to which SN 2008ha belongs originates from helium deflagrations or detonations on CO WDs rather than hybrid CONe WDs (Wang et al. 2013; Neunteufel et al. 2017). If that were the case, our model would only contribute to part of the 2002cx-like SN subclass.

The contribution of SN Ia-CSM objects to all SNe Ia is still unclear. SN 2002ic-like SNe contribute about 1% to all SNe Ia (Aldering et al. 2006), but the contribution of SN Ia-CSM objects to all SNe Ia is higher than that of SN 2002ic-like SNe since SN 1997cy and SN 1999E have also been classified as SN Ia-CSM objects. Considering that the number of discovered SN Ia-CSM objects is smaller than that of 2002cx-like SNe and that SN Ia-CSM objects are relatively more easily discovered because of their higher luminosities, the contribution of SN Ia-CSM objects to all SNe Ia is probably less than that of 2002cx-like SNe. We conclude that SN Ia-CSM objects roughly contribute between 1% and 5% of all SNe Ia. This estimate is also consistent with our estimate on the ratio of SNe Ia with and without massive CEs. Therefore, the contribution of 2002cx-like and SN Ia-CSM objects to all SNe Ia is also consistent with our estimate for SNe Ia with hybrid CONe WDs.

### 4.2. The Scale of the CSM

Figure 5 shows the distribution of CE masses at the moment when $M_{\text{WD}} = 1.378 M_\odot$. As we argued before, the interaction of the supernova ejecta with the CSM produced by massive CEs may partly contribute to the high luminosity of SNe Ia-CSM. Observations suggest that there can be a time delay between the supernova explosion and the interaction with the CSM of up to tens of days after the explosion (Hamuy et al. 2003; Aldering et al. 2006; Dilday et al. 2012; Silverman et al. 2013; Soker 2017). This seems to require a time delay between the moment when $M_{\text{WD}} = 1.378 M_\odot$ and the supernova explosion, and that the time delay must be long enough to eject the CE in some cases. Using our estimates for the CE mass and the mass-loss rate when $M_{\text{WD}} = 1.378 M_\odot$, we find that it will take $10^4$ yr to a few $10^5$ yr to eject the CE. A possible mechanism for the time delay is the spin-up/spin-down model (Justham 2011; Di Stefano & Kilic 2012), in which a rapidly rotating super-Chandrasekhar WD experiences a spin-down phase before the supernova explosion. Although the spin-down timescale, is currently not yet understood from a purely theoretical point of view, empirically it has been estimated to be between $10^3$ yr and a few $10^5$ yr, much longer than the timescale required to eject the CE (Di Stefano & Kilic 2012; Meng & Podsiadlowski 2013).

The spatial scale of the CSM formed by the final dissipation of a CE depends on the spin-down timescale, $\tau_{sd}$, and the wind velocity, $v_w$. The wind velocity in the CEW model is uncertain but is plausibly in the range of 10–100 km s$^{-1}$, likely higher than the typical wind velocity of AGB stars due to the extra gravity from the companion, e.g., a higher escape velocity from the surface of the CE (Meng & Podsiadlowski 2017). A spin-down timescale of a few $10^3$ yr and a wind velocity of $10$ km s$^{-1}$ would put the outer boundary of the CSM at a distance of $v_w \times \tau_{sd} \gtrsim 10^5$ au. The inner boundary depends on how the CE is dissipated. As the CE is much larger than the final orbit, some of it is likely to remain bound and ultimately form a circumbinary disk-like structure (perhaps similar to what is seen around AGB binaries; e.g., Bujarrabal et al. 2013). The inner boundary could then be anywhere between a few times the final orbital separation and several astronomical units, i.e., the radius of the CE (depending on the angular momentum...
stored in the remnant CE). Simply taking a terminal ejecta velocity of 30,000 km s\(^{-1}\) (Wang et al. 2006), the ejecta may interact with the CSM immediately or within one day. Similarly, assuming a spin-down timescale of a few 10\(^6\) yr and a wind velocity of 100 km s\(^{-1}\), the ejecta may catch up with the CSM within tens of days after the explosion. The estimate of the onset time of the interaction is consistent with observations (Silverman et al. 2013). Therefore, to explain the time delay between the supernova explosion and the interaction with the CSM, a spin-down timescale of \(10^6\) yr is favored, which is consistent with the constraint derived in Meng & Podsiadlowski (2013). The estimate for the spatial scale of the CSM for SN Ia-CSM objects is based on the CE mass and mass-loss rate when \(M_{\text{WD}} = 1.378 M_\odot\). This mass-loss rate is limited by the Eddington luminosity of WDs in the standard CEW model. However, during the spin-down phase, it is possible in principle to drive a super-Eddington wind and hence a higher mass-loss rate, leading to a denser CSM. On the other hand, the companion may continue to feed material to the CE during the spin-down phase, and therefore the final amount of the CSM around SN Ia-CSM objects could be larger than that shown in Figure 5. While the mass of the CSM around SN Ia-CSM objects from observations is model-dependent, it may cover a large range since the total luminosity and the decline rate of light curves differ significantly for different SNe Ia-CSM: see, e.g., SN 2005gj, 2002ic, and PTF11kx (Hamuy et al. 2003; Aldering et al. 2006; Dilday et al. 2012). In our CEW model, the amount of CE mass ranges from \(10^6 M_\odot\) to more than \(2 M_\odot\), peaking around \(1 M_\odot\). The distribution provides a potential statistical test for our SN Ia-CSM model. The detailed shape of the CSM in the CEW model is highly uncertain as it depends on numerous uncertainties in the current version of the model. A structure similar to what is seen in planetary nebulae (PNe) is possible, maybe with multiple thin shells as are often seen in PNe due to binary effects (Mastrodemos & Morris 1999; Soker 2005). In addition, for a Chandrasekhar-mass WD, RN-like eruptions may occur and lead to the formation of multiple-shell structures in the CSM. Observationally, some SNe Ia are associated with PNe, e.g., exploding inside PNe (Tsebrenko & Soker 2015; Cikota et al. 2017), and some supernova remnants even show a special “ear” structure that may be expected from CE evolution (Tsebrenko & Soker 2015). Our model could explain these observations in principle and especially the multiple thin shells detected in PTF11kx, which had previously been associated with a symbiotic system (Dilday et al. 2012). 4.3. SNe Ia-CSM Besides belonging to a young population and showing a 1991T-like spectrum, SNe Ia-CSM have relatively long light curve rise times, large peak luminosities, and potentially show evidence for dust formation at late times (Silverman et al. 2013). Our model may potentially explain all these characteristics of SNe Ia-CSM. In our model, SNe Ia-CSM are the explosions of hybrid CONe WDs with massive CEs, in which strong hydrogen emission lines are predicted from the collision of the supernova ejecta with the CSM formed from the CE. At the same time, with the expansion and cooling of the CE, dust may form around the progenitor system (Lü et al. 2013). Such dust formation in the circumstellar environment is also observed in some normal SNe Ia (Wang 2005; Goobar 2008; Johansson et al. 2013). For SNe Ia-CSM, the high luminosity is very likely correlated with the long rise time as has been demonstrated for 2002cx-like SNe Ia (Magee et al. 2016). However, for SNe Ia-CSM, the origin of the correlation could be more complex. Definitely, the collision between supernova ejecta and the CSM partly contribute to the high luminosity and long rise time of SNe Ia-CSM (Hamuy et al. 2003). In addition, the high peak luminosity could imply a high production of \(^{56}\text{Ni}\) in SNe Ia-CSM. For example, if SNe Ia-CSM originate from the hybrid CONe WDs with massive CEs, i.e., the systems with massive companions, the CONe WDs experience a relatively shorter cooling time from the birth of the WDs to the onset of accretion than those without massive CE due to their more massive companion (cf. Figure 4), i.e., the average cooling times for SNe with and without massive CEs are 0.21 Gyr and 0.44 Gyr, respectively. Such a difference of average cooling times could even imply that SNe Ia-CSM tend to trigger central ignition, while 2002cx-like SNe Ia may favor off-center ignition (Chen et al. 2014). Moreover, the shorter cooling time leads to a lower central density when the explosion occurs (Podsiadlowski et al. 2008; Chen et al. 2014). A lower central density might mean a smaller region suitable to trigger explosive carbon ignition in the center of the CONe WDs, which results in a larger production of \(^{56}\text{Ni}\), even higher than from CO WDs (Willcox et al. 2016). 4.4. 2002cx-like Supernovae Recently, Jha (2017) summarized the properties of 2002cx-like SNe: (1) the population forms quite a heterogeneous class, e.g., spanning a wide range of peak photometric luminosities; (2) 2002cx-like SNe have a spectrum similar to SN 1991T, but a luminosity similar to SN 1991bg; (3) they are preferentially found in late-type galaxies, indicating a young population; (4) they are characterized by a lower ejecta velocity compared with normal SNe Ia, and (5) 2002cx-like SNe Ia are likely to contribute to about 5% of all SNe Ia (although this estimate is very uncertain). SNe Ia from hybrid CONe WDs could in principle display significant heterogeneity, similar to what is seen in 2002cx-like SNe Ia. For one thing, the difference of the CO core mass in the hybrid CONe WDs could partly contribute to the difference in their peak luminosity, since the carbon abundance may affect the brightness of SNe Ia (Nomoto et al. 2003). In addition, whether a detonation develops after the initial deflagration phase or not may also contribute significantly to their heterogeneity. Even if a detonation develops, the explosions of hybrid CONe WDs also show differences depending on the different CO core mass and the different number of ignition regions (Bravo et al. 2016; Willcox et al. 2016). For a lower carbon abundance compared with normal CO WDs, SNe Ia from hybrid CONe WDs may have a lower luminosity and lower ejecta velocities (Nomoto et al. 2003; Bravo et al. 2016), consistent with 2002-cx-like SNe Ia. In addition, SNe Ia from hybrid CONe WDs are younger than 1 Gyr—they may even be as young as 30 Myr, consistent with 2002cx-like SNe Ia (Meng & Podsiadlowski 2014). Our estimated rate of SNe Ia from hybrid CONe WDs match the rate of 2002cx-like SNe (see Section 4.1). Therefore, the properties of 2002cx-like SNe Ia could—in principle—be reproduced by our model.
Observationally, some 2002cx-like SNe Ia show evidence for helium in their spectra (Foley et al. 2013). Based on their detailed BPS simulations, Meng & Podsiadlowski (2014) found that some MS companions become helium-rich when the CONe WD + MS systems form, which could explain the observed helium in some 2002cx-like SNe Ia. In addition, in the case of SN 2012Z, pre-supernova observations showed the presence of a luminous blue object that did not disappear after the explosion (McCully et al. 2014; Jha 2017); this is consistent with the CONe WD + He star channel (Wang et al. 2014), although BPS simulations do not reproduce the system properties in detail. In our CEW model, the companion may become almost a “naked” helium core after envelope ejection, and the helium core may be as massive as 0.97 $M_\odot$ (see Figure 4 and discussions in Meng & Podsiadlowski 2017). If helium is ignited in the companion’s center before the supernova explosion, such a companion could fit the observations of the star associated with SN 2012Z. Whether the companion may reproduce the properties of the star associated with SN 2012Z or not will heavily depend on the spin-down timescale, an issue we will address in detail in the future.

### 4.5. Hybrid/single Supernovae

In this paper, we suggest a new kind of thermonuclear explosion from single CONe WDs in an AGB-like CE, i.e., an SN I 1/2 in the nomenclature of Iben & Renzini (1983), which shows hybrid properties of CC SNe and SNe Ia. In the case where all the envelope is ejected before the supernova explosion, the explosion could be from a single CONe WD. Although the detailed properties of such explosions are difficult to ascertain, we can still speculate on some of their unusual characteristics. First, compared with the normal AGB stars, the mergers would experience a higher mass-loss rate as it is enhanced by rapid rotation (Soker 1998; Politano et al. 2008); this is helpful for explaining why the progenitors of some SNe Ia-CSM experience very high mass loss (Silverman et al. 2013). The amount of CSM mass around such SNe may be as high as $\sim 3 M_\odot$, and the CSM could possibly take the form of a dense torus or disk structure (Taam & Ricker 2010; Ohlmann et al. 2016), as deduced from X-ray observations in the case of SN 2012ca (Bochenek et al. 2018). In addition, since the CONe WDs may continue to increase their mass during the spin-down phase, the exploding CONe WD could be super-Chandrasekhar objects. Interestingly, the late-time optical and infrared spectra of SN 2012ca show low [Fe III]/[Fe II] ratios and strong [Ca II] lines, which are characteristics of the super-Chandrasekhar-mass candidate SN 2009dc (Taubenberger et al. 2013; Fox et al. 2015). Finally, for hybrid explosions originating from the merger of a CONe WD + MS system, no surviving companion would exist in the supernova remnant after the supernova explosion, which, in principle, could explain the fact that no surviving companion has yet convincingly been identified in any supernova remnant (Kerzendorf et al. 2012, 2014; Schaefer & Pagnotta 2012). However, such special SNe Ia are rare and only contribute to less than 0.03% of all SNe Ia according to our current BPS simulations and are therefore unlikely to explain the lack of identified surviving companions in the majority of cases.

In summary, we propose that both SN 2002cx-like and SN Ia-CSM objects share the same origin, i.e., from the hybrid CONe WD + MS systems. In addition, we predict a hybrid object that shows features of both SNe II and SNe Ia, but without a surviving companion. As a final caveat, we note that this discussion is based on the CEW model as presented in Meng & Podsiadlowski (2017), which is still under development (see the detailed discussions in Meng & Podsiadlowski 2017), and the model still needs to be verified by observations. On the other hand, if future observations support the suggestion proposed in this paper, it could provide support for the CEW model.

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**References**

Aldering, G., Antilogus, P., Bailey, S., et al. 2006, ApJ, 650, 510
Ashall, C., Mazzali, P., Sasdelli, M., & Prentice, S. J. 2016, MNRAS, 460, 3529
Benetti, S., Cappellaro, E., Turatto, M., et al. 2006, ApJL, 653, L129
Bochenek, C. D., Dwarkadas, V. V., Silverman, J. M., et al. 2018, MNRAS, 473, 336
Bravo, E., Gil-Pons, P., Gutiérrez, J. L., & Doherty, C. L. 2016, A&A, 589, A38
Bujarrabal, V., Alcolea, J., Van Winckel, H., Santander-García, M., & Castro-Carrizo, A. 2013, A&A, 557, A104
Cameron, E. 2011, PASA, 28, 128
Cescutti, G., & Kobayashi, C. 2017, A&A, 607, A23
Chen, M. C., Herwig, F., Denissenkov, P. A., & Paxton, B. 2014, MNRAS, 440, 1274
Chen, X., Han, Z., & Meng, X. 2014, MNRAS, 438, 3358
Chomiuk, L., Soderberg, A. M., Chevalier, R. A., et al. 2016, ApJ, 821, 119
Cikota, A., Fatat, F., Cikota, S., Sypromilo, J., & Rau, G. 2017, MNRAS, 471, 2111
Denissenkov, P. A., Herwig, F., Truran, J. W., & Paxton, B. 2013, ApJ, 772, 37
Di Stefano, R., & Kilic, M. 2012, ApJ, 759, 56
Di Stefano, R., Voss, R., & Claey, J. S. W. 2011, ApJL, 738, L1
Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, Sci, 337, 942
Folatelli, G., Challis, P. J., Chornock, R., et al. 2013, ApJ, 765, 57
Fox, O. D., Silverman, J. M., Filippenko, A. V., et al. 2015, MNRAS, 447, 772
Ge, H., Webbink, R. F., Chen, X., & Han, Z. 2015, ApJ, 812, 40
Goobar, A. 2008, ApJL, 686, L103
Graur, O., Bianco, F. B., Modjaz, M., et al. 2017, ApJ, 837, 121
Hachisu, I., Kato, M., & Nomoto, K. 1996, ApJL, 470, L97
Hachisu, I., Kato, M., & Nomoto, K. 1999, ApJ, 522, 487
Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 2003, Natuir, 424, 651
Han, Z., & Podsiadlowski, P. 2004, MNRAS, 350, 1301
Hillebrandt, W., & Niemeyer, J. C. 2000, ARA&A, 38, 191
Hjellming, M. S., & Webbink, R. F. 1987, ApJ, 318, 794
Hoyle, F., & Fowler, W. A. 1960, ApJ, 132, 565
Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897
Iben, I., & Renzini, A. 1983, ARA&A, 21, 271
Iben, I., & Tutukov, A. V. 1984, ApJS, 54, 335
Inserra, C., Fraser, M., Smartt, S. J., Scalzo, R., et al. 2016, MNRAS, 459, L51
Jha, S. 2017, in Handbook of Supernovae, ed. A. Alsubti & F. Mardin (Cham: Springer), 375
Johansson, J., Amanullah, R., & Goobar, A. 2013, MNRAS, 433, L43
Justham, S. 2011, ApJL, 730, L34
Kerzendorf, W. E., Childress, M., Scharwächter, J., Do, T., & Schmidt, B. P. 2014, ApJ, 782, 27
Kerzendorf, W. E., Schmidt, B. P., Laird, J. B., Podsiadlowski, P., & Bessell, M. S. 2012, ApJ, 759, 7
