Possible Contribution of Magnetized White Dwarf Binaries to Type Ia Supernova Populations

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Abstract

The evolution of an accreting white dwarf (WD) with a strong magnetic field toward a Type Ia supernova (SN Ia) may differ from the classical single-degenerate (SD) channel. In this paper, we perform binary population synthesis simulations for the SD channel with a main-sequence (MS) companion, including the strongly magnetized WD accretion. Under a reasonable assumption that the fraction of such systems is ~15%, the resulting delay-time distribution roughly follows the \( t^{-1} \) power-law distribution. Within the (WD/MS) SD channel, the contribution from the highly magnetized WD is estimated to be comparable to that from the classical, non-magnetized WD channel. The contribution of the SD channel toward SNe Ia can be at least ~30% among the whole SN Ia population. We suggest that the SNe Ia resulting from the highly magnetized WD systems would not share the observational properties expected for the classical SD channel; for every (potentially peculiar) SN observationally associated with the SD channel, we expect a comparable number of the “hidden” SD population to be in the normal class.

Unified Astronomy Thesaurus concepts: Type Ia supernovae (1728); Supernovae (1668); Close binary stars (254); White dwarf stars (1799)

1. Introduction

Type Ia supernovae (SNe Ia) are an excellent distance indicator used in cosmological measurement, as well as an important iron contributor in chemical evolution (Greggio & Renzini 1983; Riess et al. 1998). Despite their importance, the origin of SNe Ia is largely obscured (Hillebrandt & Niemeyer 2000; Maeda & Terada 2016; Livio & Mazzali 2018). A thermonuclear explosion of a carbon–oxygen white dwarf (CO WD) in a close binary system has been widely accepted as the origin for SNe Ia (Holey & Folwer 1960; Tutukov & Yungelson 1979; Webbink 1984). Two scenarios have been discussed as the main channel(s) toward SNe Ia. In the double-degenerate (DD) channel, two WDs merge by energy and angular momentum loss due to the gravitational-wave radiation (Iben & Tutukov 1984; Webbink 1984). In the single-degenerate (SD) channel, the WD accretes matter from its non-degenerate companion star and grows in mass to the Chandrasekhar mass (Whelan & Iben 1973; Nomoto 1982; Di Stefano et al. 2011).

The SN Ia birth rate and delay-time (from the star formation to the SN Ia explosion) distribution (DTD) place strong constraints on the SN Ia progenitor evolution (e.g., Wang & Han 2012; Maoz et al. 2014). The observationally inferred DTD indicates a power-law function with an index of ~1 (Maoz & Mannucci 2012), and it spans from the “prompt” (young) component with delay times less than 0.1 Gyr (Mannucci et al. 2006; Aubourg et al. 2008) and the “delayed” component with delay times \( \geq 2–3 \) Gyr (Botticella et al. 2008; Totani et al. 2008). Schawinski (2009) analyzed 21 nearby SNe Ia in early-type galaxies, and demonstrated a lack of young SNe Ia in these early-type galaxies by deriving the minimum delay times from 0.28 to 1.25 Gyr in their SNe Ia sample.

The DD channel has been argued to naturally produce the power-law DTD. On the other hand, it has sometimes been regarded as a challenge for the SD channel. There are a few characteristic evolutionary timescales in the SD scenario set by the nature of the donor/companion stars; main-sequence (MS), red giant (RG), or even He stars. Generally, the MS system and the RG system are suggested to be responsible for the (relatively) young and old populations, respectively (Kobayashi & Nomoto 2009). The He donor channel has been suggested to create the young(est) (or “prompt”) population (Wang et al. 2009; Claeyts et al. 2014). As such, it might not be straightforward to explain the power-law DTD as a combination of these different evolutionary channels within the SD scenario (but see Kobayashi et al. 2019).

Indeed, the young SN Ia population is generally missing in most progenitor evolution models (Ilkiv & Soker 2012; Maoz et al. 2014; Ablimit et al. 2016; Soker 2019); this does not seem to be reconciled by various uncertainties involved in the binary population synthesis (BPS) simulations (Jorgensen et al. 1997; Yungelson & Livio 2000; Wang et al. 2009; Ablimit et al. 2016). The SD (with the H-rich donor) generally predicts delay times longer than ~1 Gyr (e.g., Lü et al. 2009; Wang & Han 2012; Claeyts et al. 2014). This might be an important constraint on the contribution of the SD channel within the whole SN Ia population. Assuming a combination of the SD channel and another channel, with the latter having the power-law DTD (e.g., the prediction by the DD scenario), if the fraction of the SD is large, then this lack of a young population should be reflected in the combined DTD. This would affect the observationally inferred DTD. Adding the He donor contribution would be a solution, but this might require a fine-tuning of the relative contributions from the H-rich donors and He-rich donors.

Given the diversity seen in observational properties of SNe Ia, it is likely that multiple progenitor channels are realized in nature. There have been observational indications that a few individual classes of peculiar SNe are associated with the SD scenario (Section 3.3; see also Maeda & Terada 2016). It is thus important to understand the contribution of the SD channel.

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to the normal and whole populations of SNe Ia. The WD+MS channel is one of the more important contributors among the SD scenarios. The WD+MS channel has three different evolution pathways (see Wang & Han 2012 for more details). (1) When the primordial primary is in the Hertzsprung gap or first giant branch stage, it can fill its Roche lobe, and the two stars may evolve into the common envelope (CE) due to a large mass ratio or a convective envelope of the mass donor star. After the CE ejection and end of He burning of the primary, the CO WD can be formed with the MS companion. This channel is realized for the following initial parameters; the initial primary mass $M_{1,i} \sim 4.0\text{--}7.0\, M_\odot$, the initial mass ratio $q = M_{2,i}/M_{1,i} \sim 0.3\text{--}0.4$; and the initial orbital period $\log P \sim 1.0\text{--}1.5$ in days. (2) When the primary evolves to the early asymptotic giant branch, a CE may be formed due to the dynamically unstable mass transfer. After the CE ejection and end of He burning of the primary, the WD+MS system is produced. This channel is for the following initial parameters: $M_{1,i} \sim 3.0\text{--}6.5\, M_\odot$, $q = M_{2,i}/M_{1,i} \sim 0.2\text{--}0.7$, and $\log P \sim 2.5\text{--}3.5$ (e.g., Wang 2018). (3) The mass transfer could be dynamically unstable and a CE could be formed when the primary evolves to the thermal pulsing asymptotic giant branch. After the CE ejection, a CO WD+MS system is produced. This channel is for the following initial parameters: $M_{1,i} \sim 2.5\text{--}6.5\, M_\odot$, $q = M_{2,i}/M_{1,i} \sim 0.2\text{--}0.9$, and $\log P \sim 2.0\text{--}3.0$. The first two evolution pathways are the main routes to the WD+MS channel in the SD model for the SNe Ia, and we include all of them to obtain the SNe Ia rate from the WD+MS channel.

One key physical process that might have been missing in the context of the SD scenario is the accretion under strong magnetic field (e.g., Wheeler 2012; Ablimit et al. 2014; Farhi et al. 2017). About 25% of cataclysmic variables (CVs) are magnetic (Ferrario et al. 2015). The fraction can be even higher ($\sim33\%$) according to the recent result from GAIA DR2 (Pala et al. 2019). Magnetic WDs in supersoft X-ray sources and symbiotic binaries have been discovered as well (Kahabka 1995; Sokoloski & Bildsten 1999; Osborne et al. 2001). Ablimit & Maeda (2019) studied the evolution of the magnetized WD binary toward SNe Ia under the magnetic confinement accretion model. In this paper, we use BPS simulations to investigate the possible contribution of magnetized WD/MS binaries in the SN Ia population. In Section 2, the method and models are described. The DTD and birth rate based on our models are given in Section 3. We also address the possible contributions of the magnetized WD accretion channel to the SN Ia progenitors and implications for the SN Ia diversity. Our findings are summarized in Section 4.

2. Method

2.1. The Magnetic Confinement Model

In the polar-like systems, the binary likely has a synchronous rotation without accretion disk formation (Cropper 1990). The stream of matter from the donor is captured by the magnetic field of the WD, then it follows the magnetic field lines and falls down onto the magnetic poles of the WD as an accretion column. This may affect the accretion process onto a WD and the condition for nova eruptions (Livio 1983), and may affect the mass growth of a WD toward the Chandrasekhar mass ($M_{\mathrm{Ch}}$) to form an SN Ia progenitor (Ablimit & Maeda 2019). Previous studies suggested the possibility of producing the super-Chandrasekhar mass (above $2\, M_\odot$) WDs (e.g., Das et al. 2013) supported by the strong magnetic field in the interior of a WD. However, such an effect is significant only for an extremely strong magnetic field ($10^{15} \sim 10^{17}$ G), which far exceeds the conventionally assumed values ($10^8 \sim 10^{10}$ G; see Shapiro & Teukolsky 1983). Thus, we adopt the classical Chandrasekhar mass ($M_{\mathrm{Ch}} = 1.38\, M_\odot$) in our study.

Once the magnetic column accretion takes place, it increases the density of the accreting material for a given accretion rate. Namely, the WD surface would feel locally as if the accretion rate would be higher than the mass-transfer rate from the secondary. Thanks to this increase in the local/effective accretion rate, it can accrete the material steadily for a low transfer rate that would instead lead to a nova eruption without the magnetic confinement. Ablimit & Maeda (2019) studied the WD+MS star binary evolution while taking into account this effect. They found that (1) the lower limit for the initial mass of the donor star, leading to the WD mass increasing to $M_{\mathrm{Ch}}$, can be lower than those found in previous works (e.g., Li & van den Heuvel 1997); and (2) the range of the initial orbital period of the magnetized WD binary leading to the Chandrasekhar mass WD is extended, covering from 0.3 to 25 days. The resulting parameter space for the SN Ia progenitors is substantially larger than those found in previous work (see Ablimit & Maeda 2019 for details).

2.2. Binary Population Synthesis

We perform a series of Monte-Carlo simulations for the WD/MS binary evolution, using the binary stellar evolution (BSE) population synthesis code (Hurley et al. 2002). In this BPS calculation, $10^7$ binary systems are followed from the initial MS/MS configuration through their evolutions. The systems that end up forming a Chandrasekhar- mass WD through the accretion from a secondary MS are tagged as SN Ia progenitors. Note that we have not considered WD/RS (red giant) systems in this study. Note also that the BPS code follows the evolution of individual binary systems explicitly, and a modification has been made in the treatment of the mass accretion efficiency for the highly magnetized WD according to Ablimit & Maeda (2019; see Section 2 of that paper). Our recipe to compute the mass transfer is as follows (see Ablimit & Maeda 2019 for more details): H-burning efficiency (as well as He-burning efficiency) is determined by the RLOF mass transfer $\dot{M}$ in the classical model without the magnetic field. For the highly magnetized WD, we replace $\dot{M}$ with the polar mass transfer $(\dot{M}_p)$ in computing the burning (and thus accretion) efficiency. This efficiency is multiplied to the mass transfer $(\dot{M})$ to obtain the mass accretion rate to the primary WD.

The initial input parameters of the primordial binaries are set as follows. The initial mass function of Kroupa et al. (1993) is adopted for the masses of the primary stars. The masses of the secondary stars are determined by the distribution of the mass ratio of the secondary to the primary, which is set to be flat between 0 and 1. All stars are assumed to be initially in binaries. The distribution of the orbital separations is assumed to be flat in logarithm. The uniform (flat) initial eccentricity distribution is assumed to be in a range between 0 and 1. We set the initial metallicity of stars to be the solar value. In calculating the Galactic SN rate, we simply assume a constant star formation rate of $5\, M_\odot\, \text{yr}^{-1}$ (Willems & Kolb 2004). For the other parameters, the default values adopted in the original
BSE population synthesis code (Hurley et al. 2002) are used in this paper. Given the total mass $M_{\text{total}}$ in the simulation and the initial sets of $\phi(M_1, M_2, a)$ (where $M_1$, $M_2$ and $a$ are the primary star mass, companion star mass and binary separation, and $\phi$ is the distributions of them), the DTD is computed as follows:

$$
\text{DTD}(t) \sim \int_{M_1} \int_{M_2} \int_a \frac{1}{M_{\text{total}}} f(\text{SN Ia}) \phi \times (M_1, M_2, a) dM_1 dM_2 da.
$$

If the binary does not make an SN Ia, then $\delta(\text{SN Ia}) = 0$. When the binary produces an SN Ia during a time interval between $t$ and $t + \Delta t$, $\delta(\text{SN Ia}) = 1$.

The details of our BPS code have been described by Ablimit et al. (2016) and Ablimit & Maeda (2018). Compared to the original code by Hurley et al. (2002), we have updated the treatment of the mass transfer and the CE evolution. As in other BPS works, the fate of the CE phase is determined by the CE ejection efficiency ($\alpha_{\text{CE}}$) and the binding energy parameter ($\lambda$). The CE efficiency, $\alpha_{\text{CE}}$, is taken to be 1.0 in this paper. For the binding energy parameter, we use $\lambda = \lambda_g$ (which includes the contributions of the gravitational energy, internal energy, and entropy of the envelope; Wang et al. 2016). Note that only the gravitational energy is counted in many BPS works ($\lambda = \lambda_g$); we will briefly address how this affects the outcome of the binary evolution. In this paper, we fix the BPS parameters (such as the mass ratio distribution), adopting typical values frequently used for these parameters; our main aim in this paper is to demonstrate the potential importance of the highly magnetized magnetic WDs toward SNe Ia. There are intensive studies in the general BPS framework on the rate of SNe Ia that explore how the BPS parameters affect the outcomes (e.g., Claeyts et al. 2014; Ablimit et al. 2016). We have adopted a very simple star formation rate in our study for the same reason.

We focus on two models in the BPS calculations, Model non-B and Model high-B. All WD/MS binaries are assumed to be non-magnetic WD binaries in Model non-B. In discussing the shape of the DTD, we assume all WDs are born with the high magnetic field in the WD/MS binaries in Model high-B, while the other parameters are set to be the same with Model non-B. In order to clearly show the possible contribution of the magnetic confinement model, we adopt the same typical initial conditions in BPS calculations.

When we discuss the contribution of Model high-B to the total SN rate as combined with Model non-B, we will adopt 15% as the fraction of highly magnetized WDs. Around 25% of WDs have a magnetic field among the known CVs, and about 15%–18% are poles based on the observational results of Ferrario et al. (2015); see also Kepler et al. (2013, 2015). Pala et al. (2019) analyzed a sample of 42 CVs within 150 pc based on the GAIA DR2 survey data, and they found that the fraction of magnetic CVs in the volume-limited sample is remarkably high (33%). In their sample, the fraction of poles is $\sim 28\%$. These studies suggest that the evolution of magnetic systems has to be included in the WD binary population models. We conservatively assume that the fraction of polar-like systems among the WD binary population is 15%. When we discuss the contribution of the WD/MS SD channel to the SN Ia populations, we thus combine Model non-B and Model high-B with the fractions of 85% and 15%, respectively.

### 3. Results

#### 3.1. The Delay Time Distribution

The distribution of the time interval between the star formation and SNe Ia explosion (i.e., DTD) is a basic feature characterizing the nature of SNe Ia progenitors. Observationally, the DTD can be obtained by associating the rate of SNe Ia to the age of the host galaxies (Totani et al. 2008; Maoz & Mannucci 2012) or that of the local SN site (Maoz & Badenes 2010). Figure 1 shows the observationally inferred DTD (Maoz & Mannucci 2012). We can extract the DTD in the BPS simulation; it is the SN rate versus the time passed from a brief burst of star formation that formed a unit of stellar mass. For a given stellar mass formed by a single burst, we count the number of systems in which the primary WD reaches $M_{\text{CE}}$, with the delay time between $t$ and $t + \Delta t$ (see Section 2.2).

Figure 1 shows the DTD based on our models. We first briefly address the effect of the CE prescription, namely the binding energy parameter; it is not a main focus of this paper, but this affects the outcome of our reference Model non-B. For the same Model non-B, we simulate an additional model where we set $\lambda = \lambda_g$ (which includes only the gravitational potential energy). The delay times of SNe Ia from this model ($\lambda g$) are distributed from $\sim 0.3$ and $\sim 3.1$ Gyr. SNe Ia with relatively long delay times are realized with $\lambda = \lambda_g$. Because $\lambda_g$ leads to a higher efficiency in ejecting the CE, the binaries can survive the CE more easily (Ablimit et al. 2016). While this effect results in a relatively large SN rate in Model non-B, the contributions of DTDs from the non-B model are still largely consistent with previous BPS works (see Section 1).

The young SN Ia population with a delay time less than $\sim 0.1$ Gyr is missing in Model non-B, as is consistent with previous works (e.g., Wang & Han 2012; Claeyts et al. 2014). Model high-B results in a larger range of delay times (between...
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3.2. The Birth Rate

The birth rate of SNe Ia in the Milky Way galaxy \((\sim 3 \times 10^{-3} \text{yr}^{-1}; \text{Cappellaro & Turatto 1997})\) is an important constraint on the SNe Ia progenitor models. Figure 2 shows the Galactic birth rate of the SNe Ia found in our models. Model non-B results in the Galactic birth rate of \(\sim 6.8 \times 10^{-3} (1 - f_{B}) \text{yr}^{-1}\), where \(f_{B}\) is the fraction of highly magnetized WDs in the accreting systems. As a reference, Model non-B with \(\lambda_{s}\) for the binding energy parameter results in \(\sim 3.1 \times 10^{-4} (1 - f_{B}) \text{yr}^{-1}\). The calculated rate from the WD/MS channel without the magnetic field confinement is consistent with a range of birth rate derived by previous works (Wang & Han 2012; Claeyss et al. 2014).

The rate found in Model high-B is \(\sim 3.3 \times 10^{-3} f_{B} \text{yr}^{-1}\). Assuming the fiducial value \(f_{B} = 0.15\), as combined with Model non-B (with 85% contribution), the predicted total rate is \(\sim 1.1 \times 10^{-3} \text{yr}^{-1}\). The contributions from Model non-B and Model high-B are comparable, i.e., roughly \(\sim 5 \times 10^{-4} \text{yr}^{-1}\) for each. The rate of the “young” population within Model high-B is \(\sim 5 \times 10^{-5} \text{yr}^{-1}\), and it is also the case for the “old” population from Model high-B.

The total SN Ia rate through the WD/MS channel studied in this paper \((\sim 1.1 \times 10^{-3} \text{yr}^{-1})\) can thus account for one-third of the Galactic SN Ia rate \((\sim 10^{-3} \text{yr}^{-1})\). Given that we omit the WD/RG channel (therefore the old population) in this study, the SD channel could provide a major contribution to the SN Ia rate. The “young” and “old” populations arising from Model high-B have contributions of \(\sim 10\%\) to the total SN Ia rate in the WD/MS SD channel (as a combination of Model non-B and high-B), or \(\sim 3\%\) of the observationally inferred Galactic SN Ia rate. The remaining fraction accounts for the “intermediate” population, which dominates the SNe Ia in the present study (note that all SNe Ia from Model non-B belong to the intermediate population). Note, however, that these fractions depend on the definition of the “young” and “old” populations, thus these values should be taken merely as a rough estimate. Furthermore, the value here for the “old” population should not be directly compared to any observational indication, as we do not include the WD/RG channel.

3.3. Implications for Sub-classes of SNe Ia

While SN Ia progenitors in Model high-B evolve through the WD/MS SD channel, the nature of the progenitor systems may be quite different from the classical SD channel (i.e., Model non-B). Below, we summarize the expected nature of the progenitor systems; the SN itself evolved through Model high-B. Possible relations to observed sub-classes of SNe Ia will then be discussed.

Figure 3 shows distributions of final masses of companion stars just before the SN explosion. Overall, Model high-B is characterized by a lack of a massive MS companion star with \(> 1.8 M_{\odot}\). Because the high-mass stars drive the system into the CE in Model high-B, the massive companion stars are missing. Therefore, the detection of the companion star, either in pre-SN images of extragalactic SNe or within SN remnants, is more difficult than Model non-B. Generally, the younger population, in terms of the delay time, tends to have a more massive companion star. For the old population with a delay time exceeding \(\sim 4 \text{Gyr}\), the companion stars are all less massive than \(\sim 0.8 M_{\odot}\), down to \(\sim 0.3 M_{\odot}\).
There have been a few reports about non-detection of the companion stars (Li et al. 2011a; González Hernández et al. 2012; Kelly et al. 2014), but there is only one case where the upper limit could be sufficiently deep to probe a companion star in Model high-B (Schaefer & Pagnotta 2012). Even in this case, the companion star expected in the “old” population (but in the WD/MS channel) would not have been detected.

Figure 3 also shows the distribution of the “solid angle” of a companion as viewed from the SN ejecta, i.e., the ratio of the companion radius to the binary separation. Note that we consider only the WD/MS channel and do not include the WD/RG systems toward SNe Ia. The donors in our simulations experience either Case A or early Case B RLOF mass transfer. It has been suggested that hydrodynamical interaction between the expanding SN ejecta and a companion’s envelope should provide additional heat to the SN ejecta, which is then lost as a blue UV/optical emission in a few days (Kasen 2010). The solid angle is a measure of the strength and frequency of such a bright precursor. As shown in Figure 3, companion stars in Model high-B are substantially more compact relative to the binary separation than those in Model non-B. Therefore, we do not expect a strong signal for this companion interaction in SNe Ia evolved through Model high-B. Similarly, the amount of the hydrogen-rich companion envelope stripped into the SN ejecta (Marietta et al. 2000) will be smaller in Model high-B; the non-detection of Balmer series in late-time spectra of normal SNe Ia has been an argument against the SD channel (Mattila et al. 2005; Maeda et al. 2014; Tucker et al. 2019), but this constraint would also be weakened for Model high-B.

Observationally, SNe Ia showing possible early blue enhancement are relatively rare. The bright SNe 1991T/1999aa-like SNe Ia tend to show such emission (Stritzinger et al. 2018). However, it has been suggested that this would likely originate in a different mechanism, e.g., a mixing of $^{56}$Ni out to the surface (Maeda et al. 2018). This is further complicated because there is another mechanism, the He detonation on the surface, which could result in a signature similar to the companion interaction (Jiang et al. 2017; Noebauer et al. 2017; Maeda et al. 2018; De et al. 2019). So far, there is only a single SN Ia where the early blue emission has been attributed to the companion interaction (Cao et al. 2015), indicating the existence of an SD (but non-B) channel. The prediction from model high-B could be largely consistent with the reality of such signals in normal SNe Ia.

The nature of the progenitor WD may also be different between Model high-B and (classical) Model non-B. In the classical SD model, the disk accretion would supply angular momentum to the WD, and the WD spin would likely be kept high. The WD may even evolve toward the Chandrasekhar mass with the critical rotation (Uenishi et al. 2003; Yoon & Langer 2004). This may introduce some diversity into the angular momentum, and perhaps even the mass, of the progenitor WD. Furthermore, this may delay the explosion of the WD by the spin-down timescale (Hachisu et al. 2012), again introducing uncertainty and possible diversity into the progenitor WD system. On the other hand, the spin of the WD progenitor in Model high-B may be negligible, as a large fraction of the WD glow through the polar accretion. As such, the nature of the SN Ia progenitors in Model high-B is likely more uniform than that in model non-B. Therefore, the nature of the progenitor through Model high-B may form a relatively uniform system compared to Model non-B. However, we emphasize that this is speculative, and it will require further investigation of detailed evolution simulations of the highly magnetized WD binaries, including the rotation and magnetic field, to lead to conclusive arguments.

Because the WDs in Model high-B tend to evolve with a low mass-transfer rate, the mass budget that can be potentially ejected into the circumstellar environment is also small. Therefore, we do not expect the existence of massive and dense CSM around the SN Ia progenitors. The mass-transfer rate is typically $\sim 10^{-8} M_\odot$ yr$^{-1}$, and the fraction of the mass ejected to the environment is expected to be small. As such, the system could easily accommodate the upper limit on the CSM density derived for some (normal) SNe Ia (Chomiuk et al. 2012; Margutti et al. 2012; Maeda et al. 2015).

Overall, the natures of the progenitors and explosions expected in model high-B may indeed have similarities to
those expected in the DD channel, rather than the classical SD channel. Recently, there are indications that some outliers may be related to the SD channel, while normal SNe Ia tend not to show any signatures expected in the (classical) SD scenario in terms of the companion and the CSM environment (see Maeda & Terada 2016 for a review).

SNe Ia that have been suggested to be linked to the SD channel include the following classes: bright SN 1991T/1999aa-like SNe Ia, overluminous SNe Ia (i.e., “super-Chandrasekhar candidates”), and SNe Iax. SN 1991T/1999aa-like SNe Ia are associated with a class of “SNe Ia-CSM” (Dilday et al. 2012; Leloudas et al. 2015), which show a distinct signature of massive CSM around the progenitor system. Similarly, at least one of the overluminous SNe Ia (SN 2012dn) shows a clear signature of dusty CS environment (Yamanaka et al. 2016; Nagao et al. 2017). These indications of massive and dense CSM suggest that at least a fraction of these bright SNe Ia are better explained by the (classical) SD channel. The same argument then applied to conclude that they are not likely products through Model high-B.

Another peculiar class of SNe Iax (Jha 2017, for a review) has been suggested as an outcome of the SD channel, indirectly through its young environment (Foley et al. 2009) and a good match of the SN properties to the prediction by a specific model of a failed/weak deflagration model (Kromer et al. 2013), and directly through the detection of a possible companion star for SN Iax 2012Z in a pre-SN image (McCully et al. 2014). The companion candidate of SN 2012Z is a blue object, and suggested to be a He star; it is thus not readily associated with the scenario proposed here.

The fraction of SN1991T/1999aa-like bright SNe Ia in the volume-limited sample account for ∼9% of the total SN Ia rate (Li et al. 2011a). The overluminous SNe Ia are rare, and their contribution to the total SN Ia rate is negligible compared to that of 1991T/1999aa-like SNe Ia. Therefore, at least ∼9% of the observed SNe Ia have a possible counterpart in the (H-accreting) SD evolution channel. This suggests that there could be a comparable number of “normal” SNe evolved through the “hidden” SD channel (i.e., Model high-B), which would be identified preferentially as the DD channel in terms of nature of the CSM and companion star. Interestingly, our model predicts that for every potential SN Ia with the distinct nature of the classical SD channel (Model non-B), there should be a similar number of normal-looking SNe Ia evolved through the SD channel under the magnetic field confinement (Model high-B). As a combination, the contribution of the SD channel could be non-negligible even in normal SNe Ia. Note, however, that addressing the properties of the highly magnetized progenitor WD just before the explosions, and thus the nature of SNe Ia in Model high-B, requires further, detailed investigations.

4. Summary

The evolution of an accreting WD with a strong magnetic field may differ from the classical SD channel (Ablimit & Maeda 2019): the WD could steadily accrete the material from a donor to the Chandrasekhar mass even at a low mass-transfer rate, which would instead result in nova eruptions in the classical SD model. As a result, the parameter space for the SN Ia progenitors is different. Less massive donors spanning a larger range of the orbital period lead to an SN Ia explosion than in the classical SD channel.

In this paper, we have focused on the WD/MS systems and performed BPS simulations. The DTD from the accreting magnetic WD evolution toward the SN Ia progenitors spans a larger range of delay times than the classical SD scenario; it ranges from ∼0.06 to ∼11 Gyr. Under the reasonable assumption that a fraction of the highly magnetic WD is ∼15%, the resulting DTD roughly follows the $r^{-1}$ power-law distribution. As such, the contribution of the SD channel toward SNe Ia can be as large as ∼50% among the whole SN Ia population, without a major impact on the shape of the resulting DTD.

Within the (WD/MS) SD channel, the contribution from the highly magnetized WD has been estimated to be comparable to that from the classical, non-magnetized WD channel. According to the BPS study, the sum of these contributions reaches ∼30% of the observed Galactic SN Ia rate. Adding the WD/RG channel (i.e., Yungelson et al. 1995; Lü et al. 2009), the SD channel therefore easily explains that at least half of the total SN Ia rate.

The nature of the progenitor systems in the magnetic SD channel should probably resemble DD products more than classical SD products. They are expected to be associated with faint companion stars and a rarefied CS environment. Further investigation is required to address the detailed properties of the immediate progenitor WD, and thus the nature of the resulting SNe, but we speculate that they have a rather uniform nature in the immediate progenitor WD, and thus in the SN ejecta. As such, it is likely that they would not be identified as “SD” candidates through various observational constraints. Therefore, for every (potentially peculiar) SN observationally associated with the SD channel, we expect a comparable number of the “hidden” SD population to appear in the normal class.

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References

Ablimit, I., & Maeda, K. 2018, ApJ, 866, 151
Ablimit, I., & Maeda, K. 2019, ApJ, 871, 31
Ablimit, I., Maeda, K., & Li, X.-D. 2016, ApJ, 826, 53
Ablimit, I., Xu, X.-J., & Li, X.-D. 2014, ApJ, 780, 80
Aubourg, E., Tojeiro, R., Jimenez, R., et al. 2008, A&A, 492, 631
Botticella, M. T., Riello, M., Cappellaro, E., et al. 2008, A&A, 479, 49
Cao, Y., Kulkarni, S. R., Howell, D. A., et al. 2015, Natur, 521, 328
Cappellaro, E., & Turatto, M. 1997, in Proc. NATO Advanced Study Institute 486, Thermonuclear Supernovae, ed. P. Ruiz-Lapuente, R. Cannal, & J. Isern (Dordrecht: Kluwer), 77
Chomiuk, L., Soderberg, A. M., Poe, M., et al. 2012, ApJ, 750, 164
Claeys, J. S. W., Pols, O. R., Izzard, R. G., Vink, J., & Verbunt, F. W. M. 2014, A&A, 563, 83
Cropper, M. 1990, SSRv, 54, 195
Das, U., Mukhopadhyay, B., & Rao, A. R. 2013, ApJL, 767, L14
De, K., Kasliwal, M. M., Polin, A., et al. 2019, ApJ, 873, 18
Di Stefano, R., Voss, R., & Claey, S. J. W. 2011, ApJL, 738, L1
Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, Sci, 337, 942
Farhi, J., Fossati, L., Wheatley, B. D., et al. 2017, arXiv:1709.08266v2
Ferrario, L., de Martino, D., & Gnsicke, B. T. 2015, SSRv, 191, 111F
Foley, R. J., Chornock, R., Filippenko, A. V., et al. 2009, AJ, 138, 376
