RATES AND DELAY TIMES OF TYPE Ia SUPERNOVAE

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ABSTRACT

We analyze the evolution of binary stars to calculate synthetic rates and delay times of the most promising Type Ia Supernovae (SNe Ia) progenitors. We present and discuss evolutionary scenarios in which a white dwarf (WD) reaches the Chandrasekhar mass and potentially explodes in a SNe Ia. We consider Double Degenerate (DDS; merger of two WDs), Single Degenerate (SDS; WD accreting from H-rich companion), and AM Canum Venaticorum (AM CVn; WD accreting from He-rich companion) scenarios. The results are presented for two different star formation histories: burst (elliptical-like galaxies) and continuous (spiral-like galaxies). It is found that delay times for the DDS in our standard model (with common envelope efficiency αCE = 1) follow a power-law distribution. For the SDS we note a wide range of delay times, while AM CVn progenitors produce a short burst of SNe Ia at early times. The DDS median delay time falls between ~0.5 and 1 Gyr; the SDS between ~2 and 3 Gyr; and the AM CVn between ~0.8 and 0.6 Gyr depending on the assumed αCE. For a Milky-Way-like (MW-like) galaxy, we estimate the rates of SNe Ia arising from different progenitors as: ~10−4 yr−1 for the SDS and AM CVn, and ~10−3 yr−1 for the DDS. We point out that only the rates for two merging carbon–oxygen WDs, the only systems found in the DDS, are consistent with the observed rates for typical MW-like spirals. We also note that DDS progenitors are the dominant population in elliptical galaxies. The fact that the delay time distribution for the DDS follows a power law implies more SNe Ia (per unit mass) in young rather than in aged populations. Our results do not exclude other scenarios, but strongly indicate that the DDS is the dominant channel generating SNe Ia in spiral galaxies, at least in the framework of our adopted evolutionary models. Since it is believed that WD mergers cannot produce a thermonuclear explosion given the current understanding of accreting WDs, either the evolutionary calculations along with accretion physics are incorrect, or the explosion calculations are inaccurate and need to be revisited.

Key words: binaries: close – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Type Ia Supernovae (SNe Ia) play an important role in astrophysics as cosmological distance indicators. Additionally, they provide iron peak elements, having direct consequences for the chemical evolution of galaxies (Riess et al. 1995; Matteucci & Greggio 1986; de Donder & Vanbeveren 2003). Currently, >2000 SNe Ia have been observationally confirmed some as distant as z~1.55 (Strømger et al. 2004). Empirically derived relationships between light curve properties and intrinsic luminosity (i.e., Δm15, Phillips 1993, and stretch factor s, Perlmutter et al. 1997) have made it possible to “standardize” absolute magnitudes of SNe Ia light curves over a wide variety of host galaxy environments. Their use as “standard candles” on cosmological scales has led to the realization that the expansion rate of the universe is accelerating, and has enabled accurate estimations of ΩΛ and ΩM (e.g., Schmidt et al. 1998; Riess et al. 1998; Perlmutter et al. 1999). However, using SNe Ia in order to set the distance scale for the determination of cosmological quantities requires the (still unfounded) assumption that the physical properties of their progenitors are unchanging with redshift.

Despite the continued use of SNe Ia as standard candle distance indicators, their origin remains uncertain. It is generally accepted that SNe Ia arise from the total disruption of a Chandrasekhar mass (~1.4 M⊙) carbon–oxygen white dwarf (WD) as a result of thermonuclear explosion. This hypothesis is supported by the fact that the amount of energy observed in the explosions (~1051 erg; Thielemann et al. 2004) is equal to the amount which would be produced in the conversion of carbon and oxygen into iron (see, e.g., Livio 2000, for a review). It is natural to presume that the exploding WD must accrete matter from a close stellar companion until reaching the critical Chandrasekhar mass, though the nature of the companion, the rate and efficiency at which mass is accumulated onto the WD, and which array of conditions are necessary in order for the WD to ignite explosively, are not well understood (Nomoto et al. 1997).

In order to constrain the nature of SN Ia progenitors, the SN Ia rate has been studied as a function of parent galaxy stellar mass, star formation rate (SFR), color, morphology, and radio power by several groups (e.g., Mannucci et al. 2005; Sullivan et al. 2006; Calura & Matteucci 2006; Della Valle & Panagia 2003). Mannucci et al. (2005) found that the SN Ia rate is higher in bluer, later type galaxies, supporting the hypothesis that there is a non-negligible number of SNe Ia originating from young progenitors. Sullivan et al. (2006) found that the SN Ia rate per unit mass increases as a function of star formation activity, a trend which coincides with the results of Calura & Matteucci (2006), who used chemical evolution models to derive

4 Predoctoral Fellow
5 Oppenheimer Fellow
6 http://www.cfa.harvard.edu/iau/lists/Supernovae.html
7 It has been shown that SNe Ia originating among young stellar populations are overall more luminous than those associated with older stellar populations (i.e., Hamuy et al. 1995).
the rate of SNe Ia as a function of galaxy Hubble type. Della Valle & Panagia (2003) discovered an enhanced SN Ia rate in radio-loud galaxies compared to their radio-quiet counterparts, possibly as a result of past interactions/mergers with dwarf galaxy companions leading to an increased number of newly formed or captured young stars (see also Della Valle et al. 2005). The evolution of the SN rate (both core-collapse and Type Ia) as a function of cosmic time was investigated by Madura et al. (1998), who convolved a set of theoretical characteristic SN delay times with the cosmic star formation history, resulting in an estimate of SN rates out to intermediate redshifts. Later studies showed that a single-component delay time could not be reconciled with the observed mass of iron in galaxy clusters and the corresponding ratio of core-collapse to Ia SN rates (Maoz & Gal-Yam 2004).

SNe Ia are observed in both young and old galaxies (Branch & van den Bergh 1993), thus it is natural to presume that the progenitors may originate from both young and old stellar populations. Recently, it has been found that SNe Ia appear to span a wide range of delay times which is bimodal in nature, consisting of a “prompt” population with short delay times, and a “tardy” population whose average delay time distribution (DTD) is much wider and is best described by a decaying exponential function (Scannapieco & Bildsten 2005; Mannucci et al. 2006; Dilday et al. 2008). However, whether the apparent bimodal DTD shape is limited to low-redshift SNe alone or whether it also applies to SNe at higher redshift is still unclear (Dahlen et al. 2008).

Two formation scenarios have emerged as the most likely channels for SNe Ia progenitors: the Single Degenerate Scenario (SDS; Whelan & Iben 1973; Nomoto 1982) and the Double Degenerate Scenario (DDS; Iben & Tutukov 1984; Webbink 1984). The SDS is encountered when a WD accretes H-rich matter during stable Roche Lobe Overflow (RLOF) from a stellar companion; either a main-sequence or an evolved (giant) star. The WD increases in mass up to the Chandrasekhar-mass limit, enabling carbon to ignite explosively in the WD center causing an SN Ia. The DDS is the result of a merger of two WDs. If the combined mass of the merger exceeds the Chandrasekhar mass, the result may be an SN Ia. Additionally, it has been suggested that a third channel, the AM CVn channel,8 may account for 1% of SNe Ia (Solheim & Yungelson 2005). AM CVn binaries (see, e.g., Nelemans 2005; Warner 1995) are ultracompact systems involving a WD accretor and a helium-rich donor exchanging matter via RLOF. The donors are expected to be small stars given the small orbital size (close orbits; ≤ 1 hr). Other possible SNe Ia formation scenarios have been proposed, though they likely do not account for the majority of SNe Ia (e.g., sub-Chandrasekhar-mass SNe Ia, Woosley & Weaver 1994; common envelope (CE) WD mergers, Livio & Riess 2003; Applegate 1991; Sparks & Stecher 1974).

In this study, we follow the evolution of stellar populations in two different environments, which is typical for an elliptical galaxy (instantaneous burst of star formation at t = 0) and that typical for a spiral galaxy (continuous star formation). We also employ two different parameterizations for CE evolution. To substantiate our conclusions, we use exactly the same total stellar mass and metallicity for each population; the only differences in our model galaxies are the star formation histories, and the assumed CE removal efficiency αCE. We show which SN Ia progenitors are the most likely (from an evolutionary perspective) for each host galaxy type, and derive delay times and rates for the most promising SNe Ia progenitor scenarios. We compare our results to those of previous studies and we discuss our results (e.g., in terms of explosion physics) in the last two sections, respectively.

2. MODEL DESCRIPTION

Our stellar evolution calculations are performed using the StarTrack population synthesis code. A detailed description of the input physics is presented in Belczynski et al. (2002, 2008). Single star evolution is followed from the ZAMS until remnant formation employing modified analytic formulæ and evolutionary tracks from Hurley et al. (2000). Evolution of binary stars is more complex, and several processes important for field binary evolution are accounted for, such as tidal interactions, mass transfer phases, CE evolution, SN kicks, magnetic braking, and gravitational radiation (see Belczynski et al. 2008, for formulæ). We incorporate recent prescriptions for mass growth of WDs, employing accretor mass-dependent accumulation efficiencies which may lead to nova explosions, stable burning, or optically thick WD winds (Nomoto et al. 2007; Kato & Hachisu 2004; Hachisu et al. 1999; Kato & Hachisu 1999; Priulnik & Kovetz 1995; Hashimoto et al. 1986, see below). The physical properties of the stars are computed throughout the evolution.

A merger between two WDs may lead to a DDS SN Ia. A detached WD–WD binary will eventually reach contact due to angular momentum loss from the emission of gravitational radiation, and if the binary configuration (e.g., mass ratio) leads to a merger, the less-massive WD is accreted onto the more-massive WD (see, e.g., Tutukov & Yungelson 1979). If the combined mass of the merger exceeds the Chandrasekhar mass, it is recorded as a potential DDS SN Ia progenitor. We assume a priori that every WD–WD merger with M > 1.4 M⊙ consisting of CO–CO, CO–He, or He–He WDs leads to an instantaneous SN Ia.9 Mergers involving other WD types occur in our simulations but we do not count them as SN Ia progenitors.

An SDS or AM CVn SN Ia may result from the accumulation of matter on a WD’s surface via stable RLOF from a stellar companion. For accretion of hydrogen-rich material, strong nova explosions inhibit the accumulation of hydrogen on the WD surface for very low mass transfer rates < 10−11 yr−1 (Priulnik & Kovetz 1995). For mass transfer rates above this threshold, we interpolate over the results of Priulnik & Kovetz (1995) to obtain the mass accretion efficiencies, and we account for optically thick winds at high mass transfer rates (Hachisu et al. 1999; see also Belczynski et al. 2005, Section 2.3, for a more detailed description). The only difference between the accumulation efficiencies in this work and those of Belczynski et al. (2005) is that here we have additionally included an updated prescription for accretion of hydrogen-rich matter from Nomoto et al. (2007), in which fully efficient accumulation is only achieved for a very narrow range of mass transfer rates, and is also dependent upon the WD accretor mass (Nomoto et al. 2007, see Equations (5) and (6)).

Accretion of helium-rich matter is treated in the same fashion as in Belczynski et al. (2005): accretion prescriptions are adopted from Kato & Hachisu (1999). However, this study contains one major difference which affects our results: though in

8 SWB-like in Belczynski et al. (2005).

9 In Belczynski et al. (2005), it was assumed that a merger between any two WDs, including ONe WDs, with a combined mass exceeding 1.4 M⊙, would lead to an SN Ia, though CO–CO mergers made up 88% of the DDS SNe Ia in that study.
this work we do allow for the formation of sub-Chandrasekhar-mass SNe Ia, we do not include these binaries as potential SN Ia progenitors here. In Belczynski et al. (2005), a large fraction (61%) of the Type Ia SNe which contributed to the presented delay times in the standard model were in fact sub-Chandrasekhar SNe Ia, in which the accumulation of $\sim 0.1 \, M_\odot$ of He-rich material on the WD surface could lead to an edge-lit detonation and subsequent SN Ia (Woosley & Weaver 1994; Kato & Hachisu 1999).

The criteria used here for defining SNe Ia progenitors arising from different formation channels are different from the work of Belczynski et al. (2005). In this work, we only consider accreting WDs which have obtained a mass of $1.4 \, M_\odot$ as potential SNe Ia. We make the distinction between SN Ia progenitors with CO WDs accreting from nondegenerate hydrogen-rich companions (SDS), and WDs accreting from helium-rich companions (AM CVn). We note that He WDs never reach the Chandrasekhar mass in our simulations with the adopted accumulation physics, and we have assumed that oxygen–neon–magnesium WDs collapse to form a neutron star (accretion-induced collapse) upon reaching the Chandrasekhar mass, rather than producing an SN Ia (e.g., Miyaji et al. 1980). For the SDS and AM CVn cases, we record the binary as an SN Ia once the accreting WD has reached the Chandrasekhar mass. The SDS may occur when a WD accretes matter via RLOF from any hydrogen-rich companion (e.g., main-sequence or evolved star). If the WD accumulates enough hydrogen on its surface such that steady burning can occur, the WD can increase in mass up to $1.4 \, M_\odot$, carbon ignites explosively in the WD center and the result is an SN Ia. In the AM CVn scenario, we assume the result is an SN Ia if the CO WD reaches $1.4 \, M_\odot$ via stable RLOF from a helium-rich companion. We allow for different types of helium-rich donors in the AM CVn scenario: helium stars (non-degenerate stars burning helium in the core or in a shell which have been stripped of their outer hydrogen envelope), helium WDs, and hybrid WDs (CO-rich core, helium-rich mantle).

We adopt two contrasting SFRs: an instantaneous burst at $t = 0$ (elliptical galaxy) and a constant SFR for 10 Gyr (spiral galaxy). Both populations are then evolved up to 15 Gyr. The mass formed in stars in both cases is the same: $6 \times 10^{10} \, M_\odot$, which corresponds to the stellar mass in the Milky Way (MW; Klypin et al. 2002). In each population we adopt a binary fraction of 50% (2/3 stars in binaries), though this fraction may be overestimating the binary population among low-mass stars (Lada 2006), and underestimating the binary fraction among massive stars (Kobulnicky & Fryer 2007). All stars are evolved with solar-like metallicity ($Z = 0.02$). While the initial distributions representative of the physical characteristics of ZAMS binaries, and the correct way in which to treat CE evolution and magnetic braking are all somewhat uncertain, our choices for various distribution functions are constrained by available observations (see below). The magnetic braking prescription which we adopt is that of Ivanova & Taam (2003), which is based on a two-component coronal model (see Section 3.2 of Belczynski et al. 2008).

ZAMS masses ($M_{\text{ZAMS}}$) span the entire mass range: $0.08$–$150 \, M_\odot$. Single stars and binary primaries are drawn from a three-component broken power-law initial mass function (Kroupa et al. 1993), and secondary masses are obtained from a flat mass ratio distribution (Mazeh et al. 1992; $q =$ secondary/primary), which is the canonical choice among population synthesis studies (Lü et al. 2006). However, given the observational selection effects, the true mass ratio distribution among ZAMS binaries remains unknown, though it is likely dependent upon stellar mass (Trimble 1990; Duqunnoy & Mayor 1991). It has been suggested that the mass ratio distribution among local spectroscopic field binaries as well as young early-type stars is peaked near unity (Fisher et al. 2005; Kobulnicky & Fryer 2007). Initial orbital separations in our calculations span a wide range up to $10^5 \, R_\odot$ and are drawn from a distribution $\propto 1/a$ (Abt 1983), which has been found to be representative of the local population of Hipparcos binaries (Lépine & Bongiorno 2007). Initial eccentricities are drawn from a distribution $\Psi(e) = 2e$ (Duqunnoy & Mayor 1991).

Close binaries (and potential SN Ia progenitors) are believed to encounter a phase of CE evolution, and this remains one of the most poorly understood phases in stellar astrophysics. For this reason, we present the delay times and rates of SNe Ia for two different CE parameterizations. Some comparison between different prescriptions for CE evolution have been tested against observations for local double WDs (Nelemans & Tout 2005). It is unclear at this point how the CE phase should best be treated in population synthesis studies, and currently detailed models are not sophisticated enough to explore the parameter space in detail (Ricker & Taam 2008). For this work, we choose the “$\alpha$” prescription for CE evolution (Webbink 1984), in which the orbital energy of the binary is used to unbind the CE from the system. We choose two different values for the parameterization of CE removal efficiency $\alpha_{\text{CE}}$. For our standard model (Model 1) we choose $\alpha_{\text{CE}} \times \lambda = 1$, where $\lambda$ is a function of the donor envelope structure, and is of order unity (see also van der Sluys et al. 2006). As an alternative, we additionally include a model with decreased CE removal efficiency in which $\alpha_{\text{CE}} \times \lambda = 0.5$ (Model 2).

3. DELAY TIMES

Model 1: $\alpha_{\text{CE}} \times \lambda = 1$. We use the elliptical model, with all stars born at $t = 0$ to demonstrate the DTD for the various progenitors. Figure 1 (top panel) shows the characteristic delay times for Model 1, and the average and median delay times of all three progenitors are also indicated. The sharp cutoff near 15 Gyr is artificial, as evolution was only allowed to proceed for 15 Gyr.

The DDS events follow a power-law–like DTD, with a median of $t_{\text{mod}} = 0.93$ Gyr and approximated functional form of $f(t) \propto 10^{-t}$. Only a small fraction $\sim 5\%$ are “prompt” (Mannucci et al. 2006) events with delay times $t < 100$ Myr. The DDS events are expected to be found long after the star formation has ceased ($t \sim 10$–15 Gyr) therefore we expect these progenitors to produce SNe Ia both in young (spiral and starburst) and old (elliptical and bulges) host populations. Even though we have allowed DDS progenitors to arise from mergers between any combination of CO and/or He WDs, all of our DDS systems originate from mergers of CO–CO WD binaries, since mergers of He–He or CO–He WD binaries never exceed $1.4 \, M_\odot$. The evolution leading to the formation of a CO–CO WD binary usually starts with two intermediate-mass stars ($M_{\text{ZAMS}} \sim 3$–$9 \, M_\odot$) that evolve through a series of close interactions, the first one typically being stable RLOF and the last one being a CE phase. Once a CO–CO WD is formed, the dominant mechanism for angular momentum loss is gravitational radiation, the merger timescale $t_{\text{GR}} \propto a^{-\nu}$ (Peters 1964). Given the initial distribution of orbital separations $\propto a^{-1}$, and the evolutionary orbital change that is to first order the same for all DDS progenitors (reduction of orbital size by a factor of $\sim 10$–100 during the CE phase), the
due to gravitational radiation: initial distribution and the change in separation which occurs

\[ t \sim g(t) = 100 \, t^{-1} \]

and follows the DTD reasonably well. Bottom panel: Model 2, DDS progenitor systems which survive the CE phase.

\( \lambda_{\text{CE}} \times \lambda = 5.2 \), versus that of Model 1 (\( \lambda_{\text{CE}} \times \lambda = 1.0 \)). The DTD for Model 2 is shown in Figure 1 (bottom panel). The change in the treatment of the CE evolution leads to smaller orbital separations after the CE phase, which affects the subsequent binary evolution and thus leaves an imprint on the resulting DTD.

As with Model 1, Model 2 DDS progenitors involve only CO–CO WD binaries. However, with the decreased CE efficiency, many potential DDS progenitors merge before a detached WD binary has been produced, thus there is a lack of DDS progenitors and there is an increase in the number of merging WD + AGB core systems. The same power-law curve from the top panel of Figure 1 is shown for comparison. The power-law-like shape of the DDS is present in Model 2 for delay times \( \lesssim 6 \) Gyr with an additional pile-up of progenitors at short delay times (\( t \lesssim 1 \) Gyr). The pile-up is due to the fact that in Model 2, DDS progenitor systems which survive the CE phase (e.g., binaries which do not merge in the CE) are on closer orbits upon emerging from the CE, thus they merge with relatively shorter delay times (\( t_{\text{GR}} \propto d^3 \)). This “shift” to earlier delay times in the DTD from Model 1 to Model 2 serves to build a relatively stronger peak at short delay times, while at the same time decreases the number of DDS progenitors with delay times \( \gtrsim 1 \) Gyr. This is the reason for the shorter median delay time in Model 2: \( t_{\text{Med}} = 0.52 \), versus that of Model 1 (\( t_{\text{Med}} = 0.93 \)).

The SDS channel of Model 2 is more efficient than that of Model 1 since the WD and the stellar companion are brought on a closer orbit during the CE phase. For this reason, wider systems which would have evolved to become double WDs (e.g., AM CVn double degenerates) in Model 1 evolve into binaries with WDs accreting from nondegenerate companions in Model 2. In Model 2, the contribution of main-sequence donors in the SDS channel is slightly higher since after the CE and formation of a CO WD, in many cases the stars are close enough for the secondary to fill its Roche lobe before
evolving off of main sequence. The number of SDS progenitors involving main-sequence donors is doubled relative to Model 1 and now constitutes 10% of the total SDS population (90% are giant or subgiant companions). SDS progenitors originate from systems with donor masses $\sim 0.7 M_\odot < M_{ZAMS} < 2.7 M_\odot$, many of which are $M_{ZAMS} > 1.25 M_\odot$ thus have main-sequence lifetimes shorter than $5$ Gyr. The increased number of SDS progenitors at earlier delay times leads to a decrease in the SDS median delay time from $\sim 3.2$ Gyr (Model 1) to $\sim 2.1$ (Model 2).

The DTD of the AM CVn progenitor population of Model 2 is notably different from that of Model 1, in that it is bimodal. The “fast” channel at delay times $\lesssim 3$ Gyr is still present, and originates from progenitors with donor masses $M_{ZAMS} \gtrsim 2.5 M_\odot$ which undergo two CE events. However, in Model 2, the decreased orbital separation of post-CE binaries allows for the formation of a new SN Ia progenitor channel, in which a CO WD initially accretes hydrogen from a low-mass main-sequence star for several Gyr, as the main-sequence star continues to fuse hydrogen into helium in its core (see also Podsiadlowski et al. 2008). The main-sequence star, which has been losing its outer layers in RLOF, has built up a significant helium core by the time its lifetime is still present, or an SN Ia, in a Hubble time.

4. RATES

Assuming a binary fraction of 50%, as we have done in this study, 0.17% and 0.09% of stellar systems (where a “system” represents either a single star for a binary) evolve into SN Ia in Models 1 and 2, respectively. For an assumed binary fraction of 100%, 0.34%, and 0.18% of binaries evolve into SN Ia in Models 1 and 2, respectively. Note that this applies to both elliptical and spiral populations as they differ only in SFR but not in any evolutionary parameters other than $\alpha_{CE} \times \lambda$. The above fractions translate into integrated efficiencies of 1 SN Ia per 2500 $M_\odot$ and 4700 $M_\odot$ of formed stars for Models 1 and 2, respectively, when a binary fraction of 50% is assumed. For an assumed binary fraction of 100% the integrated efficiencies are 1 SN Ia per 1500 $M_\odot$ and 1 SN Ia per 2800 $M_\odot$ for Models 1 and 2, respectively. Though the efficiency scales with the adopted binary fraction, the rates as a function of time, obviously, are different depending on the adopted SFR.

A general summary of Models 1 and 2 rates is presented in Tables 1 and 2 where we show the rate of SN Ia in SNuM, where 1 SNuM $\equiv 1$ SN (100 yr)$^{-1}$ ($10^{10} M_\odot)^{-1}$ (Mannucci et al. 2005). We show the number of SN Ia in SNuM for the three Chandrasekhar-mass models investigated in this work at four different epochs: 0.5, 3, 5, and 10 Gyr. SNuM rates are shown for our four galaxy models: elliptical, Model 1; spiral, Model 1; elliptical, Model 2; spiral, Model 2.

Model 1. In Figure 2 (top panel), SN Ia rates (number of SNe per unit time) are shown for our Model 1 elliptical galaxy ($\alpha_{CE} \times \lambda = 1$, instantaneous starburst at $t = 0$). The three progenitor types: DDS, SDS, and AM CVn are shown separately. The DDS rate declines with time, but DDS progenitors are found both at early and late times. The DDS events dominate over the other progenitor types. This dominance is very strong ($\sim 1$–2 orders of magnitude) and holds for the entire evolution of an elliptical galaxy (0–15 Gyr). The rate of SN Ia from AM CVn systems is high for times $\lesssim 2$ Gyr and then rapidly declines. Since for a typical AM CVn progenitor (1) the CO WD forms early ($t_{evol} < 100$ Myr) and with a high mass ($M_{CO, WD} \sim 1.1 M_\odot$) from primaries of initial mass $M_{ZAMS} \sim 5$–7 $M_\odot$, and (2) the orbital separation after two CEs is small, the two stars are brought into contact either by GR (He WD) or a combination of GR and evolutionary expansion (helium star). Once the donor fills its Roche Lobe, accumulation is fully efficient for binaries with main-sequence helium star

\begin{table}[h]
\centering
\caption{Rates of SNe Ia Progenitors (SNuM) for Model 1}
\begin{tabular}{|c|c|c|}
\hline
\multicolumn{3}{|c|}{Rate (100 yr)$^{-1}$ $10^{10} M_\odot)^{-1}$ as a Function of Time} \\
\hline
\hline
DDS & Elliptical & Spiral \\
\hline
0.5 Gyr & $1.6 \times 10^{-1}$ & $2.0 \times 10^{-1}$ \\
3 Gyr & $2.3 \times 10^{-2}$ & $8.0 \times 10^{-2}$ \\
5 Gyr & $1.2 \times 10^{-2}$ & $6.0 \times 10^{-2}$ \\
10 Gyr & $\gtrsim 5 \times 10^{-3}$ & $3.3 \times 10^{-2}$ \\
\hline
SDS & & \\
0.5 Gyr & $\lesssim 10^{-3}$ & 0 \\
3 Gyr & $\sim 3 \times 10^{-3}$ & $\lesssim 10^{-3}$ \\
5 Gyr & $\sim 1 \times 10^{-3}$ & $\sim 10^{-3}$ \\
10 Gyr & $\lesssim 10^{-3}$ & $\sim 10^{-3}$ \\
\hline
AM CVn & & \\
0.5 Gyr & $2.2 \times 10^{-2}$ & $\sim 10^{-2}$ \\
3 Gyr & $< 10^{-3}$ & $\sim 5 \times 10^{-3}$ \\
5 Gyr & $\lesssim 10^{-4}$ & $\sim 4 \times 10^{-3}$ \\
10 Gyr & 0 & $\sim 1 \times 10^{-3}$ \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Rates of SNe Ia Progenitors (SNuM) for Model 2}
\begin{tabular}{|c|c|c|}
\hline
\multicolumn{3}{|c|}{Rate (100 yr)$^{-1}$ $10^{10} M_\odot)^{-1}$ as a Function of Time} \\
\hline
\hline
DDS & Elliptical & Spiral \\
\hline
0.5 Gyr & $1.3 \times 10^{-1}$ & $1.3 \times 10^{-1}$ \\
3 Gyr & $\sim 5 \times 10^{-3}$ & $6.0 \times 10^{-2}$ \\
5 Gyr & $\sim 3 \times 10^{-3}$ & $3.5 \times 10^{-2}$ \\
10 Gyr & $\sim 10^{-3}$ & $1.4 \times 10^{-2}$ \\
\hline
SDS & & \\
0.5 Gyr & $\sim 2 \times 10^{-3}$ & 0 \\
3 Gyr & $\sim 5 \times 10^{-3}$ & $\sim 8 \times 10^{-3}$ \\
5 Gyr & $\sim 3 \times 10^{-3}$ & $\sim 6 \times 10^{-3}$ \\
10 Gyr & $\sim 10^{-3}$ & $\sim 3 \times 10^{-3}$ \\
\hline
AM CVn & & \\
0.5 Gyr & $\sim 5 \times 10^{-3}$ & $< 10^{-3}$ \\
3 Gyr & 0 & $\sim 10^{-3}$ \\
5 Gyr & 0 & $\sim 10^{-3}$ \\
10 Gyr & $< 10^{-4}$ & $< 10^{-3}$ \\
\hline
\end{tabular}
\end{table}
The resulting rate of potential DDS SNe Ia varies substantially with time. At early times ($t \lesssim 1$ Gyr) the rates are very high ($\sim 0.01$ yr$^{-1}$), and then they gradually decrease to reach $\sim 0.0003$ yr$^{-1}$ at late times ($t \gtrsim 10$ Gyr). The observed rates for elliptical galaxies are estimated at the level of $R_{\text{obs}} \sim 0.00018 \pm 0.0006$ yr$^{-1}$ per unit $(10^{10} M_\odot$) of blue luminosity (Cappellaro et al. 1999). As the blue luminosity of elliptical galaxies declines with time (after an early star formation episode), the rates presented in the top panel of Figure 2 should be corrected downwards at early times, while at later times they should be increased if our rates are to be compared with those of typical ellipticals. Obviously, the burst of star formation on the order of $6 \times 10^{10} M_\odot$ would produce a blue luminosity larger than $10^{10} L_\odot$ while $10$–$15$ Gyr after the episode when stars more massive than $\sim 1 M_\odot$ have formed remnants and are no longer contributing to the galaxy’s light, the blue luminosity is smaller than the normalizing value. Since we do not really know the distribution of age of the galaxies in the observed sample of ellipticals that were used in the SN Ia rate estimate, we do not attempt to correct our synthetic rates for the evolution of blue luminosity and we do not compare them directly to the observed rates of Cappellaro et al. (1999). However, we note that the observed rates is consistent with our predicted rates for the DDS progenitor, while the predicted rates for other progenitors (SDS and AM CVn) seem to be significantly too low.

In Figure 2 (bottom panel), we show the SN Ia rates for the spiral galaxy model of Model 1. It is found that DDS rates of SNe Ia at the current epoch are $0.002$ yr$^{-1}$. At first, the DDS rate increases with time (after the onset of star formation), then remains approximately constant until the star formation stops leading to an overall decline in the rate. This behavior reflects the specific shape of the DTD for the DDS combined with the SFR for our spiral galaxy model. The rates for SDS and AM CVn progenitors are much smaller and at the level of $\sim 10^{-4}$ yr$^{-1}$. SDS progenitors can generate SNe Ia long after star formation has ceased (long delay times), while AM CVn events disappear shortly after the star formation has stopped (short delay times). For comparison, overplotted are empirical rates of SNe Ia. The rates were adopted from Cappellaro et al. (1999) for a MW-type spiral (Sbc-Sd) with a blue luminosity of $2 \times 10^{10} L_\odot$, and the rates are $R_{\text{obs}} = 0.004 \pm 0.002$ SN Ia yr$^{-1}$. The DDS rate alone is consistent with the empirical rate of SNe Ia. The SDS and AM CVn SN Ia rates do not even come close to the empirical rate, and their addition to the DDS rate does not significantly affect the overall rates at any epoch. We note that our mass normalization which implies a constant star formation history for 10 Gyr results in a SFR at the level of $6 M_\odot$ yr$^{-1}$. The global SFR in the MW may be somewhat lower: $\sim 3.5 M_\odot$ yr$^{-1}$ (Cox 2000; O’Shaughnessy et al. 2008), and in that case the DDS rates are only marginally consistent with the observed Cappellaro et al. (1999) rates. On the other hand, it has been suggested that the SFR of the MW has been decreasing with time, only reaching $\sim 3.5 M_\odot$ yr$^{-1}$ at the current epoch (Nelemans et al. 2001, 2004, see Section 2.2). If such an estimate had been used the average SFR of the MW is found at the level of $\sim 8 M_\odot$ yr$^{-1}$, and our results would scale up, being consistent with the DDS scenario as the major SN Ia contributor in MW-like spiral galaxies, as long as the Cappellaro et al. (1999) rates are being used for comparison.

Model 2. There is a marked decrease, by nearly a factor of 2, in the total number of SNe Ia progenitors in our model with decreased CE removal efficiency. The overall decrease is due to the fact that the most dominant potential channel, the DDS, is only $\sim 50\%$ as efficient, since a larger fraction of binaries will merge in the CE phase rather than surviving the CE to subsequently form a double WD.

In Figure 3 (top panel), SN Ia rates are shown for our Model 2 elliptical galaxy ($\alpha_{\text{CE}} \times \lambda = 0.5$, instantaneous starburst at $t = 0$). DDS SNe Ia progenitors continue to outnumber the SDS and AM CVn progenitors, however there are some notable differences. For short delay times $t \sim 1$ Gyr, the DDS rates are
later times, the Model 2 DDS rates are a factor of nearly a factor of 2 lower than they are for Model 1. Then at later times, as in Model 1, these type of events are expected only in young host galaxies or in regions with ongoing star formation. “Fast” AM CVn progenitors are more rare in Model 2 since these systems more readily merge in one of the two CE phases that lead to the formation of these progenitors. In contrast to Model 1, there is a small contribution of the “slow” AM CVn progenitors (long delay times) in Model 2. The AM CVn channel is outnumbered by both the SDS and DDS channels at all epochs in the Model 2 elliptical galaxy.

In Figure 3 (bottom panel), SN Ia rates are shown for our Model 2 spiral galaxy. It is found that DDS rate of SNe Ia at the current epoch (10 Gyr) is 0.001 yr$^{-1}$; a factor of 2 below that of the Model 1 spiral galaxy. At first, the DDS rate increases and then remains fairly constant until star formation ceases at 10 Gyr. At all epochs (particularly during star formation), the DDS channel rates significantly outnumber the SDS and AM CVn channels, but to a lesser degree than when compared with Model 1. The SDS channel also exhibits a relatively constant rate at times later than $\sim$1 Gyr. At the current epoch the SDS rates are at the level of 0.0002 yr$^{-1}$; a factor of $\sim$5 below the DDS rates. The rates arising from AM CVn progenitors are fairly negligible at all epochs ($<10^{-4}$ yr$^{-1}$). Even when the rates from all three progenitor channels in the considered galaxy model are combined (0.0012 SNe Ia yr$^{-1}$), the SN Ia rate at the current epoch falls below the empirically derived rate from Cappellaro et al. (1999) by roughly a factor of 2.

It is worth comparing our model galaxy rates to the rates presented in Mannucci et al. (2005). In that study, Mannucci et al. (2005) derive SN rates for galaxies of various morphological types, and present the SN rates in SNUm (as inferred from K-band luminosity measurements). We cannot directly compare our rates in Tables 1 and 2 to those of Mannucci et al. (2005) since we do not know the exact ages of the galaxies in their sample. However, we note that our Model 1 elliptical galaxy SN Ia rate at 10 Gyr is 0.005 SNUm (see Table 1 DDS rates), which is nearly a factor of 10 below the SN Ia rate in E/S0 galaxies presented by Mannucci et al. (2005): 0.044$^{+0.016}_{-0.014}$ SNUm (see their Table 2). We note as well that for the same model galaxy, at $t = 500$ Myr (shortly after a burst of star formation at $t = 0$) we obtain an SN Ia rate of $\sim$0.18 SNUm (mostly via the DDS channel with some contribution from AM CVn), which is about a factor of 2 lower than the range of SN Ia rates found for star-forming Irregular galaxies in Mannucci et al. (2005; 0.77$^{+0.42}_{-0.31}$). The Mannucci et al. (2005) SN Ia rate for S0a/b spirals is found to be 0.065$^{+0.027}_{-0.025}$ SNUm, which matches our Model 1 spiral galaxy rates at 5 Gyr (0.065 SNUm; mostly DDS and AM CVn progenitors). The SN Ia rate of Sbc/d spirals from Mannucci et al. (2005) is 0.17$^{+0.068}_{-0.063}$, and matches our Model 1 spiral SN Ia rate only at very early times ($\sim$0.5–1 Gyr, see Table 1).

For the Model 2 elliptical galaxy, we find a low SN Ia rate of $\sim$0.001 SNUm at 10 Gyr, which is over an order of magnitude below the rate for E/S0 galaxies in Mannucci et al. (2005; 0.044$^{+0.016}_{-0.014}$ SNUm). The rate at 500 Myr for the same galaxy is $\sim$0.14 SNUm (see Table 2); mostly arising from DDS progenitors with some contribution from AM CVn and SDS. This rate is a factor of a few below the Ia rates for Irregular galaxies in Mannucci et al. (2005; 0.77$^{+0.42}_{-0.31}$). In comparing our Model 2 spiral rates, we find that our SN Ia rate at 3 Gyr ($\sim$0.07 SNUm; mostly DDS progenitors with some contribution from SDS) is within the range of rates presented in Mannucci et al. (2005) for S0a/b spirals (0.065$^{+0.027}_{-0.025}$), while only our spiral rates for Model 2 at very early times ($<1$ Gyr; 0.13 SNUm, DDS) are high enough to match those of Mannucci et al. (2005) for Sbc/d type galaxies (0.17$^{+0.068}_{-0.063}$). We note that in general, our rates

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**Figure 3.** Same as Figure 2 for the Model 2 stellar population. Top panel: elliptical galaxy. Bottom panel: spiral galaxy. Approximating the star formation history of the MW to be constant, the current Galactic SN Ia rate considering the DDS alone is 0.0001 yr$^{-1}$; which is below the empirical rate estimate of Cappellaro et al. (1999; 0.004 ± 0.002 yr$^{-1}$). (A color version of this figure is available in the online journal.)

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11 A typical age for local ellipticals; see Mannucci et al. (2005), Section 7.
(per unit mass) are lower than those of Mannucci et al. (2005), indicating that perhaps other channels leading to the formation of SNe Ia should be considered in evolutionary studies (e.g., single stars, sub-Chandrasekhar-mass SNe Ia). We also note however that our predicted rates as a function of time (at least for the DDS) are consistent with the observed rates presented by Cappellaro et al. (1999).

We find that in general the DDS outnumber SDS and AM CVn progenitors. This effect is somewhat more pronounced in Model 1 (a factor of \( \gtrsim 10 \)) than in Model 2 (a factor of \( \sim 5 \)), but the reason why is clear for both models. The occurrence rate of a CO–CO WD merger with a total mass \( \gtrsim 1.4 M_\odot \) (DDS) is higher than that of building up a CO WD’s mass to \( \sim 1.4 M_\odot \) via stable mass transfer (SDS) in a binary. Formation efficiencies in both of the above cases are very low, after all SNe Ia are rather rare events. However, relatively speaking it is easier to find a pair of two CO WDs (DDS), each with a mass of \( \gtrsim 0.7 M_\odot \) which is a typical mass for CO WDs, than it is for a CO WD to double its mass through accretion (SDS/AM CVn). This finding is a consequence of the recent updates on accumulation physics calculations (Hachisu et al. 1999; Kato & Hachisu 1999; Nomoto et al. 2007) that we have adopted in our evolutionary study. Basically, the accumulation onto a WD is hampered by a number of processes that tend to remove matter which is transferred from the companion in a close binary (e.g., nova explosions, He-shell flashes, optically thick winds from the surface of an accreting WD), in some cases leading to the disruption of an accreting WD before it reaches the limiting Chandrasekhar mass; i.e., accretion of \( \sim 0.1 M_\odot \) of a He-rich layer which ignites and disrupts the underlying WD (sub-Chandrasekhar-mass SN Ia, see, e.g., Kato & Hachisu 1999). Since, (1) there is a rather narrow range of mass transfer rates which may lead to efficient accumulation and (2) there are not that many binary configurations (and we have considered the entire range for our adopted evolutionary model) that can sustain mass transfer for a prolonged period of time, the SDS and AM CVn channels are found to produce SNe Ia at very low rates.

5. COMPARISON WITH OTHER STUDIES

The recent theoretical study of Hachisu et al. (2008) finds an SDS DTD which follows a power law. In their study, Hachisu et al. (2008) incorporate a new mass stripping effect (based on Hachisu et al. 1999), where in the case of high mass transfer rates the WD blows an optically thick wind strong enough to “strip” material from a main-sequence or giant donor. This effect in return stabilizes mass transfer, enabling the binary to avoid a CE phase even in the case of a relatively massive \( \sim 6 M_\odot \) donor. The result is that the WD can accrete stably up to the Chandrasekhar mass, with a wider range of potential progenitor donor ZAMS masses: 0.9–6 \( M_\odot \) in Hachisu et al. (2008) versus 0.7–2.7 \( M_\odot \) in our current study. Even though we allow for SN Ia progenitors to form from any initial mass spanning the initial mass function, our DDS SNe Ia only derive from binaries involving low-mass donors since we do not take into account this stripping effect. We note that the Hachisu et al. (2008) model predicts the presence of a thick disc of hydrogen-rich circumstellar material around the SN Ia progenitor. If such a circumstellar torus were present around the majority of progenitors of SNe Ia, one would likely expect to observe hydrogen in their spectra, though to date less than 1% of SNe Ia have shown any signature of associated hydrogen (see, e.g., Han & Podsiadlowski 2006).

Han & Podsiadlowski (2004) investigated SNe Ia progenitors from WD + MS and WD + evolved binaries with very specific binary configurations using population synthesis. In that work, they do not present rates of SNe Ia derived from other possible formation channels of SNe Ia so we cannot compare DDS rates. The Galactic rate of SDS SNe Ia for their model which most closely matches our standard (Model 1) parameters is \( \sim 6 \times 10^{-4} \text{ yr}^{-1} \). This value is an order of magnitude above our SDS spiral galaxy Model 1 rate of \( \sim 6 \times 10^{-5} \text{ yr}^{-1} \), though is still nearly an order of magnitude lower than the empirical SN Ia Galactic rate of Cappellaro et al. (1999, \( 4 \times 10^{-3} \text{ yr}^{-1} \)). The rate for the Han & Podsiadlowski (2004) model which most closely matches Model 2 is \( \sim 10^{-3} \text{ SNe Ia yr}^{-1} \), which is close (though still below) the Galactic rates of Cappellaro et al. (1999), and is a factor of 5 higher than our Model 2 SDS rates \( \sim 2 \times 10^{-4} \text{ yr}^{-1} \).

It was pointed out by Han & Podsiadlowski (2004) that their prescription for hydrogen accumulation is more efficient than that used by other authors (i.e., Yungelson & Livio 1998). It is also more efficient than the prescription we have adopted in this study. The range of hydrogen accretion rates onto WDs which leads to stable burning (see Section 2) and efficient mass accumulation is uncertain, and it is possible that stable hydrogen burning may occur for a wider range of accretion rates, in turn allowing for higher SNe Ia rates following from the SDS channel as allowed in Han & Podsiadlowski (2004). However, comparison of model hydrogen accreting WDs on the H–R diagram with supersoft X-ray sources (Nomoto et al. 2007) indicates that the prescription for stable hydrogen burning in a thin shell (and adopted here) is consistent with observations.

It is worth noting that the DTDs of Greggio (2005), derived using analytical formulations, produce a DDS DTD shape which is similar to ours: peaked at short (< 1 Gyr) delay times, followed by a smooth drop-off as a function of time, due to the dependence of the delay time on the timescale associated with gravitational wave emission. A similar trend is also found for the delay times of DDS progenitors in Yungelson & Livio (2000, Figure 2). The Greggio (2005) study also determined that the shape of the DTD arising from DDS progenitors was more flat than when compared to that of the DDS, and that the DDS delay time depended upon the main-sequence lifetime of the secondary star (see their Section 5), which is consistent with our findings.

Delay times of SNe Ia were calculated by Belczynski et al. (2005). It was found that the merger of two WDs was consistent with an empirical delay time estimate of \( \sim 3 \) Gyr (Strøgel et al. 2004), and that WDs accreting from nondegenerate stars could potentially explain the observed delay times if a low CE efficiency is used \((\alpha_{\text{CE}} \times \lambda = 0.3)\) and if it is presumed a priori that WD mergers contribute negligibly or not at all to the SNe Ia population. The above results were obtained with an earlier version of the StarTrack code; the code was recently updated to include the most recent accumulation rates (e.g., Nomoto et al. 2007). All other recent revisions relevant for low- and intermediate-mass binary evolution in the code are described in detail in Belczynski et al. (2008). Additionally, in the Belczynski et al. (2005) study, very different criteria were adopted for SNe Ia; the majority of their SNe originated from sub-Chandrasekhar-mass events and it was permitted that the merger of two WDs of any type (including ONeMg WDs) with a total mass exceeding 1.4 \( M_\odot \) led to an SN Ia. In the current study we also note that the number of sub-Chandrasekhar-mass progenitors exceed the number of Chandrasekhar-mass progenitors. The

\[12\] Delay times were computed by adopting a cosmic star formation history based on that of Madau et al. (1998).
weakness of the sub-Chandrasekhar model is that much of the outer (and fastest moving) material is believed to burn to nickel with very few intermediate mass elements (Livne & Arnett 1995). The resulting spectra do not match current observations of normal SNe, and the best fits are for subluminous SNe. Only ~6 subluminous SNe Ia were recently reported (Kasliwal et al. 2008) as compared to 36 (Riess et al. 1998) or 42 (Strolger et al. 2004) normal ones discovered only in the Hubble surveys.

6. DISCUSSION

We have evolved single and binary stars using the population synthesis code StarTrack, and have analyzed the resulting delay times (time from binary formation at \( t = 0 \) to SN Ia) of potential SNe Ia. We have considered possible SNe Ia progenitors arising from three formation channels: DDS (WD mergers), SDS (hydrogen-rich accretion on to a WD), and the AM Canum Venaticorum scenario (helium-rich accretion on to a WD). Additionally, we have computed SN Ia rates for two galaxy types: an elliptical galaxy with a starburst at \( t = 0 \) and a spiral galaxy with a constant SFR, and in each case we have tested the impact of the CE removal efficiency for two different parameterizations: \( \alpha_{CE} \times \lambda = 1 \) (Model 1), and \( \alpha_{CE} \times \lambda = 0.5 \) (Model 2).

Our SN Ia rates (century \(^{-1} \) \( (10^{10} \, M_{\odot})^{-1} \)) have been presented in Tables 1 and 2. We reiterate that the rates which we have derived in this work are “local” (no redshift evolution) rates. It is still interesting to note that in calculating the volumetric SN Ia rate out to \( z = 0.12 \) fitting the A + B model, Dilday et al. (2008) found \( A = (2.8 \pm 1.2) \times 10^{-14} \, \text{SNe Ia yr}^{-1} \, M_{\odot}^{-1} \), which is most similarly matched by our DDS Model 1 rates for MW-like spirals (\( \sim 3 \times 10^{-14} \, \text{SNe Ia yr}^{-1} \, M_{\odot}^{-1} \) at 10 Gyr). This two-component or “A+B” model (see Mannucci et al. 2006; Scannapieco & Bildsten 2005) assumes that the SN Ia rate is a function of stellar mass density and the SFR, and allows for fitting prompt and tardy SN Ia populations. We note that for Model 1 DDS progenitors dominate the overall SN Ia rates, whether it is for elliptical or spiral hosts. For Model 2, the overall rates of SNe Ia are a factor of 2 lower than in Model 1, though SNe Ia progenitors arising from the DDS and SDS channels are found in equal numbers for delay times 2.5–5.5 Gyr.

For all models considered, we expect both very short (\( \lesssim 1 \) Gyr) and long (\( \sim 10–15 \) Gyr) SN Ia delay times if they originate from DDS progenitors. Could such a population explain the bimodal distribution of delay times derived from some observations? In principle, one may expect such a result; if DDS progenitors are dominant in both old and young galaxies, the empirically derived delay times may appear to be bimodal and erroneously point toward two different progenitor populations. However, the reported bimodal DTD among SNe Ia (Mannucci et al. 2006; i.e., 50% of SNe Ia having “prompt” delay times \( \lesssim 100 \) Myr) is not reproduced in any of our models. For our standard model, only \( \sim 5\% \) of systems have delay times below 100 Myr, with 50% of our SNe Ia occurring within \( \sim 800 \) Myr since the starburst. The model which comes closest to reproducing such a bimodal DTD is the DDS channel of Model 2, where there is a large fraction of SNe Ia progenitors with short delay times (50% with \( t < 500 \) Myr). If in fact such a large fraction of SNe Ia occur within 100 Myr of star formation, it may pose a very interesting problem for binary evolution to explain. Some alternatives are already being considered, for example a single star SN Ia progenitor (Iben & Renzini 1983; Maoz 2008). To properly approach this issue one needs to fold our evolutionary calculations with the cosmic star formation history and distribution of galaxy types and mass as a function of redshift. However, it was pointed out that the constraints on observational DTDs which incorporate convolution with assumed cosmic star formation history may not be as strong as they are claimed to be (Forster et al. 2006).

For our standard (Model 1) set of evolutionary parameters, the DDS dominates (roughly 90%) the rate of Type Ia SNe in both spiral and elliptical galaxies. The rate of DDS SNe Ia is consistent with the observed SN Ia rate of Cappellaro et al. (1999). The DTD of potential DDS SNe Ia follows a smooth power-law distribution through a Hubble time. The SDS DTD is mostly flat throughout a Hubble time, while the AM CVn SNe Ia contribute events mostly at short delay times, but neither contribute significantly to the total SN Ia rate for spiral-like galaxies. The DDS DTD, following a power law, is consistent with the findings of Totani et al. (2008), whose observationally derived delay time of SNe Ia in intermediate-redshift elliptical galaxies follows a featureless power law \( \propto t^{-1} \) for \( 0.1 < t < 10 \) Gyr.

For Model 2, the DDS dominates (83%) the rate of Type Ia SNe in both spiral and elliptical galaxies. The DDS rate is below the observed SN Ia rate of Cappellaro et al. (1999) by a factor of 2. The DTD of potential DDS SNe Ia does not exhibit as strong of a power-law shape as Model 1, since relatively more WD binaries merge at early delay times, and more would-be DDS progenitors merge during the CE phase and thus never produce an SN Ia. The SDS DTD is most prominent \( \sim 2–6 \) Gyr (at which times the SDS rates match those of the DDS) and at later times the SDS contributes very little to the overall rates. The AM CVn SNe Ia contribute some events mostly at short delay times, with the rates being at a very low level at long delay times.

As noted previously, all DDS SNe Ia progenitors are the result of a merger of a CO–CO WD binary. Mergers between CO–He WDs are relatively less common than He–He or CO–CO WD mergers since often times mass transfer is stable, and upon reaching contact the CO–He binary will enter an AM CVn phase rather than coalesce. In any case, mergers of He–He or CO–He WDs are not massive enough to lead to SNe Ia, though they may lead to other very interesting phenomena, as they are likely precursors to helium burning hot subdwarfs or CRB stars (Webbink 1984). There is a marked decrease in the number of double WDs which are formed in Model 2 relative to Model 1 due to a heightened number of mergers which are encountered during the CE phase.

Typically, population synthesis calculations produce the right number of ChandraXkhar-mass WD–WD mergers, yet usually produce an order of magnitude too few SDS SNe to explain the observed rate estimates (see, e.g., Branch et al. 1995; Livio 2001; Yungelson 2005). As it turns out, most hydrodynamical WD merger calculations result in the less-massive WD being disrupted in a few orbits, causing the more-massive WD to accrete at an extremely high rate (Rasio & Shapiro 1995; Benz et al. 1989). At very high accretion rates, the WD mergers are believed to collapse to form a neutron star, not produce an SN Ia thermonuclear explosion (Mochkovitch & Livio 1990; Saio & Nomoto 1985, 1998; Woosley & Weaver 1994). Some new studies have found that some mergers might produce SNe Ia, but the merger conditions must be severely refined (Yoon et al. 2007).

Either population synthesis studies with the adopted accretion physics are missing active progenitor paths for SNe Ia, or the physics of merger calculations are incorrect. All of our results
and conclusions were based on one evolutionary model with a specific (albeit the most updated) set of accumulation rates and have been presented from the standpoint of population synthesis (i.e., thus far we have ignored the information provided by merger calculations). Yoon et al. (2007) predicted that only DDS systems with small mass ratios $q < 0.4$ can produce SN Ia explosions, while the rest will end up in accretion induced collapse and neutron star formation. If we had adopted this as an additional criterion the implications would have been rather dramatic for our results. At the time of the merger, only $\sim 0.2\%$ of the DDS systems from Model 1 (Model 2) have $q < 0.4$, since a low $q$ usually leads to stable mass transfer and not a merger. If the DDS rates had been decreased so drastically, none of our calculated SN Ia progenitors would be able to match the observed rates.

If we had relaxed our assumption on Chandrasekhar-mass explosions and we had incorporated sub-Chandrasekhar-mass explosion models—ignition of a degenerate layer of He-rich material accumulated on the surface of a WD—(Woosley & Weaver 1994; Kato & Hachisu 1999)—the Galactic rates for AM CVn would increase from $\lesssim 10^{-5}$ yr$^{-1}$ to $\sim 10^{-3}$ yr$^{-1}$ for Model 1 and to $\sim 5 \times 10^{-4}$ for Model 2. We note that in this estimate we have allowed sub-Chandrasekhar-mass explosions to occur only for WDs with masses $M_{\text{wd}} > 1 M_{\odot}$, since for lower WD masses the explosions would not look like those observed for typical SNe Ia (e.g., Hillebrandt & Niemeyer 2000).

If indeed WD mergers (DDS) cannot lead to thermonuclear explosions, one needs to consider alternatives for increasing the rates of SDS and AM CVn progenitors, either by moving away from the standard evolutionary model, or widening the range for efficient accumulation rates onto WDs.

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