Type Ia Supernovae and Accretion Induced Collapse

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Abstract.
Using the population synthesis binary evolution code `StarTrack`, we present theoretical rates and delay times of Type Ia supernovae arising from various formation channels. These channels include binaries in which the exploding white dwarf reaches the Chandrasekhar mass limit (DDS, SDS, and helium-rich donor scenario) as well as the sub-Chandrasekhar mass scenario, in which a white dwarf accretes from a helium-rich companion and explodes as a SN Ia before reaching the Chandrasekhar mass limit. We find that using a common envelope parameterization employing energy balance with $\alpha_{\rm CE} = 1$ and $\lambda = 1$, the supernova rates per unit mass (born in stars) of sub-Chandrasekhar mass SNe Ia exceed those of all other progenitor channels at epochs $t = 0.7 - 4$ Gyr for a burst of star formation at $t = 0$. Additionally, the delay time distribution of the sub-Chandrasekhar model can be divided in to two distinct evolutionary channels: the 'prompt' helium-star channel with delay times < 500 Myr, and the 'delayed' double white dwarf channel with delay times > 800 Myr spanning up to a Hubble time. These findings are in agreement with recent observationally-derived delay time distributions which predict that a large number of SNe Ia have delay times < 1 Gyr, with a significant fraction having delay times < 500 Myr. We find that the DDS channel is also able to account for the observed rates of SNe Ia. However, detailed simulations of white dwarf mergers have shown that most of these mergers will not lead to SNe Ia but rather to the formation of a neutron star via accretion-induced collapse. If this is true, our standard population synthesis model predicts that the only progenitor channel which can account for the rates of SNe Ia is the sub-Chandrasekhar mass scenario, and none of the other progenitors considered can fully account for the observed rates.

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INTRODUCTION

The progenitors of Type Ia supernovae (SNe Ia) remain unknown, though the idea that SN Ia progenitors belong to at least two distinct populations [see e.g., 1, 2, 3, 4] has recently been gaining ground. A picture is emerging which supports populations of both quickly-evolving (prompt) progenitors with short delay times less than $t \sim 500$ Myr, as well as more slowly-evolving progenitors with (sometimes rather) long delay times spanning up to a Hubble time.

The most favoured SN Ia progenitor scenarios involve the double degenerate scenario (DDS; Webbink [5]), and the single degenerate scenario (SDS; Whelan & Iben [6]). In the DDS, the merger of two carbon-oxygen (CO) white dwarfs (WDs) with a total mass exceeding the Chandrasekhar mass limit, $M_{\rm Ch} \sim 1.4\,{\rm M}_{\odot}$, can lead to explosive carbon-burning which causes a SN Ia explosion. In the SDS, a CO WD accretes from a non-degenerate stellar companion via stable Roche-lobe overflow (RLOF), enabling the WD to accumulate mass toward $M_{\rm Ch}$ until carbon is ignited explosively in the centre leading to a SN Ia. The companion filling its Roche-lobe can be hydrogen-rich or helium-rich; in this work we delineate between SDS (hydrogen-rich donors) and helium-rich donor cases, as in the latter case the donor may be a non-degenerate helium-burning star, or a degenerate helium-rich WD.

For some time, population synthesis calculations [e.g., 7] have predicted that the number of merging CO WDs (DDS) with a total mass exceeding $M_{\rm Ch}$ is sufficient to match, and thus possibly account for, the rate of SNe Ia [0.4 ± 0.2 per century for the Galaxy, 8]. At the same time, despite the fact that potential SDS progenitors have been observed [9], the theoretically-predicted SN Ia rate from the SDS channel is usually unable to explain the observed rates of SNe. In the majority of population studies, the relative frequency of SDS events is often found to be well below those of the DDS [10, 11, see also Mennekens et al. [12]] being about an order of magnitude too low compared to observations of SNe Ia.

Detailed WD merger simulations have shown that some WD mergers can successfully lead to a SN Ia explosion

[13, 14]. However, the main argument against the DDS is that the merging process leads to physical conditions in which a thermonuclear explosion is unlikely [15]. It is more probable that a merger between two CO WDs with a total mass $> M_{\rm Ch}$ will collapse and form a neutron star; an accretion induced collapse [AIC, 16]. Such events could be detectable in modern transient surveys, though would have an observational signature unlike those of SNe Ia [17].

Recently, Ruiter et al. [11] carried out a population synthesis study showing rates and delay times for SNe Ia involving WDs whose mass at the time of SN Ia had reached the Chandrasekhar mass limit: DDS, SDS and helium-rich donor scenarios ('AM CVn' channel in that work). We extend our investigation of progenitors and focus on the sub-Chandrasekhar mass model (detailed results are presented in Ruiter et al. 2010, in preparation). Since these calculations are based on the work which was performed for Ruiter et al. [11], the reader is referred to that paper for a more detailed description of the DDS, SDS and helium-rich (Chandrasekhar mass WD) donor scenario.

Sub-Chandrasekhar SNe Ia

Sub-Chandrasekhar SNe Ia – SNe Ia which take place in WDs whose mass is below $M_{\rm Ch}$ – likely consist of a (probably CO) WD accreting via stable RLOF from a helium-rich companion [18]. These systems have thus far been regarded as an unlikely model for SNe Ia owing to the fact that most synthetic light curves and spectra of these objects from previous studies did not match those of observations [e.g., 19, 20], likely owing to the thickness of the helium shell ($\sim 0.2 M_{\odot}$). More recently, Shen & Bildsten [21] have shown that conditions suitable for a detonation in the WD might be achieved for even lower helium shell masses than were assumed in previous studies. Double detonations in sub-Chandrasekhar mass WDs with low-mass helium shells have shown to be a robust explosion mechanism that can produce SNe Ia of normal brightness, provided that a detonation in the helium shell is successfully triggered [22]. Recent results involving hydrostatic sub-Chandrasekhar mass exploding WDs with subsequent nucleosynthesis and radiative transfer calculations [23, 24] indicate that the sub-Chandrasekhar mass scenario should be considered as a likely SN Ia progenitor candidate. Additionally, population synthesis studies [11] predict that there are a sufficient number of these binaries to explain the observed rate of SNe Ia.

MODEL DESCRIPTION

We use the `StarTrack` population synthesis binary evolution code [25] to evolve our stellar population. The initial distributions for binary orbital parameters (orbital periods, mass ratios, etc.) are the same as described in Ruiter et al. [11, section 2]. In Ruiter et al. [11], it was assumed that the ejection of the envelope of the mass-losing star during a CE phase came at the expense of removing the orbital energy of the binary, as dictated by the 'energy-balance' equation (or 'α-formalism') [5]

$$\frac{G\,M_{\rm don,i}\,M_{\rm ej}}{\lambda\,R_{\rm don,i}} = \alpha_{\rm CE}\left(\frac{G\,M_{\rm don,f}\,M_{\rm com}}{2\,a_{\rm f}} - \frac{G\,M_{\rm don,i}\,M_{\rm com}}{2\,a_{\rm i}}\right) \qquad (1)$$

where G is the gravitational constant, $M_{\rm don,i}$ is the initial mass of the (giant) donor star just prior to the CE, $M_{\rm ej}$ is the ejected mass (assumed to be the mass of the giant's envelope), $M_{\rm com}$ is the mass of the companion (assumed to be unchanged during the CE), $M_{\rm don,f}$ is the final mass of the donor once the envelope has been ejected, $R_{\rm don,i}$ is the initial radius of the donor star when it fills its Roche-lobe, $a_{\rm i}$ is the initial orbital separation, $a_{\rm f}$ is the final orbital separation (if $a_{\rm f}$ is too small to accommodate the Roche-lobes of the stars, the CE results in a merger), $\alpha_{\rm CE}$ is the efficiency with which the binary orbital energy can unbind the CE, and λ is a parameterization of the structure of the donor star; both $\alpha_{\rm CE}$ and λ are fairly uncertain. Here we employ $\alpha_{\rm CE} = 1$ and $\lambda = 1$. In an upcoming paper we investigate the impact of the CE parameterization on SN Ia delay times and rates (Ruiter et al. 2010, in preparation).

Sub-Chandrasekhar Mass Model

It has been shown previously that a WD accumulating helium-rich material may be capable of exploding in a Type Ia supernova if the correct conditions are satisfied; even if the WD is below the Chandrasekhar mass limit [26, 18, 27, 28]. We adopt the prescription of Ivanova & Taam [28], applied to accretion from helium-rich companions only, to determine when a particular binary undergoes a sub-Chandrasekhar mass SN Ia [25, see section 5.7.2 for equations]. In short, we consider three different accretion rate regimes for accumulation of helium-rich material on

CO WDs, adopting the input physics of Kato & Hachisu [29, 30]. At high (e.g., initial RLOF) accretion rates, helium burning is stable and thus mass accumulation on the WD is fully efficient ($\eta_{\rm acu} = 1$). At somewhat lower accretion rates, helium burning is unstable and the binary enters a helium-flash cycle, thus accumulation is possible but is not fully efficient ($\eta_{\rm acu} < 1$). In both of these aforementioned accretion regimes, the CO WD is allowed to accrete (and burn) helium, and its total mass may reach the Chandrasekhar mass limit within a Hubble time and explode as a Type Ia supernova through the helium-rich donor channel. However, for low accretion rates compressional heating at the base of the accreted helium layer plays no significant role, and a layer of unburned helium can be accumulated on the WD surface. Following Ivanova & Taam [28], we assume that if such a CO WD accumulating helium enters this 'low' accretion rate regime and accumulates $0.1 M_{\odot}$ of helium on its surface, a detonation is initiated at the base of the helium shell layer. Consequently, a detonation in the core of the CO WD is presumed to follow, and we assume that a sub-Chandrasekhar Type Ia supernova takes place. In our model, only accreting WDs with a *total mass* $> 0.9 M_{\odot}$ are considered to lead to potential sub-Chandrasekhar SNe Ia, since lower mass cores, while they may detonate, are unlikely to produce enough radioactive nickel and hence will not be visible as SNe Ia. Thus in all future discussions we refer to sub-Chandrasekhar systems whose total WD mass (CO core + helium shell) is at least $0.9 M_{\odot}$ at the time of SN Ia.

RESULTS

For an instantaneous burst of star formation at $t = 0$, we have calculated the DTD and rates of SNe Ia arising from different formation channels: the DDS, SDS, helium-rich donor, and the sub-Chandrasekhar scenario. We find that only two SN Ia formation scenarios are capable of matching the observed SNe Ia rates: the DDS and the sub-Chandrasekhar channels. The adopted sub-Chandrasekhar scenario ($M_{\rm WD} > 0.9$) is dominant at nearly all epochs ≤ 5 Gyr. As found in Ruiter et al. [11], the DDS DTD follows a continuous power-law with the largest number of events occurring starting at ~ 50 Myr. We present for the first time the DTD of the sub-Chandrasekhar mass channel, which is clearly divisible into prompt and a delayed components.

Delay Times

In Figure 1 we show the DTD of the four progenitor channels investigated in this work. We show the delay times in units of SNe Ia per year per unit stellar mass born in stars (SNuM $\times 10^{-12}$; SNuM = SNe Ia per century per $10^{10} M_{\odot}$). For our DTD normalization, we have assumed a binary fraction of 50% across the entire initial stellar mass function. We note that the bumps in the smoothed plot are due to Monte Carlo noise.

As was found in Ruiter et al. [11] Model 1, the DDS DTD follows a power-law shape with $\sim t^{-1}$, while the SDS distribution is somewhat flat with no events with delay times less than ~ 450 Myr. The reason why the SDS does not harbour prompt events is directly linked to the donor star's ZAMS mass; all SDS progenitor donors are found to have ZAMS masses below $2.8 M_{\odot}$. When the secondary ZAMS mass is $> 2.8 M_{\odot}$, the binary will enter a CE phase when the secondary fills its Roche-lobe, rather than a stable RLOF phase. In such a case, the binary will not become an SDS SN Ia, though may under the right circumstances evolve to SN Ia from the helium-rich donor channel. The helium-rich donor DTD consists mostly of systems with relatively short ($\sim$100 Myr -2 Gyr) delay times, with very few events at long delay times. We refer the reader to Ruiter et al. [11] for a description of these DTDs; The overall DTD shapes remain the same as in that work.

The sub-Chandrasekhar mass systems can easily by eye be grouped into two classes: those which occur with delay times less than ~ 500 Myr, and those with delay times above ~ 800 Myr. Not surprisingly, these two classes of SNe Ia stem from two very different evolutionary scenarios. Those with short delay times consist of progenitors which involve a helium-burning star donor, where as the rest consist of helium or hybrid (CO core, helium mantle) WD donors.

The prompt component (delay times < 500 Myr) accounts for ~ 13 % of all sub-Chandrasekhar SNe Ia that explode within 13 Gyr of star formation. Nearly all of these systems (~ 10% of the total sub-Chandrasekhar SNe) have helium star donors, with a small fraction of the prompt component originating from the hybrid WD channel. The delay time is governed by the main sequence (MS) lifetime of the donor star. The companions with ZAMS masses $\geq 3 M_{\odot}$ evolve off of the MS within ≤ 400 Myr. After the first CE, which leaves behind a CO primary WD and a MS secondary star, the (slightly evolved) secondary will fill its Roche-lobe and mass transfer is once again unstable leading to a second CE phase. The CE brings the CO WD and newly-formed naked helium star on a close orbit ($\sim 35-40$ min. orbit).

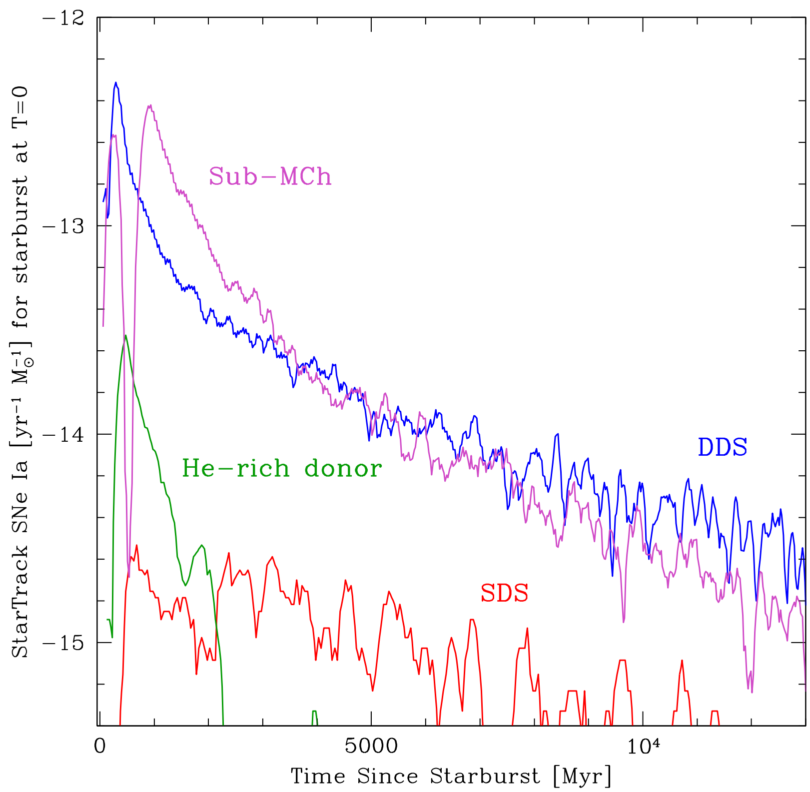

FIGURE 1. Delay time distribution. The number of SNe Ia per year per unit stellar mass born in stars (at starburst t=0, 50% binarity) is shown for the four formation channels considered: DDS, SDS, helium-rich donor, Chandrasekhar mass WD, and sub-Chandrasekhar. Despite the different scaling on the *y*-axis from Ruiter et al. [11], the shapes of the DTDs from the three Chandrasekhar (or above) mass models are the same as in that work (Model 1). The newly-calculated sub-Chandrasekhar SN Ia DTD clearly shows two distinct populations: the helium star channel (spike at delay times less than ~ 500 Myr) and the helium WD channel (from ~ 800 Myr to a Hubble time).

Within $\sim$ a few Myr the helium star fills its Roche-lobe. However, initial mass transfer rates for the helium star channel fall within the 'low accretion rate regime': typically such systems have initial mass transfer rates $\sim 2\times10^{-8} M_\odot \mathrm{yr}^{-1}$.

The delayed component (delay times > 500 Myr) comprise the other ~ 87 % of the sub-Chandrasekhar mass progenitors; binaries with helium WD donors make up ~ 78 % (the rest being hybrid WD donors). These binaries also evolve through two CE phases, as is expected for the evolution of AM CVn binaries. Similar to the DDS, the timescale governing the DTD for the helium WD channel is primarily set by the gravitational radiation timescale. However unlike the DDS, these WDs do not merge upon contact, but enter a stable phase of RLOF.

Rates

In Table 1, we show the SN Ia rates for a spike of star formation at $t = 0$, and a binary fraction of 50%. As was determined in Ruiter et al. [11], Model 1, DDS rates are able to (just) account for the observed Galactic rate of SNe Ia, where as both the SDS and helium-rich donor channels fall short by over an order of magnitude. We find that the rate of our adopted sub-Chandrasekhar SN Ia model exceeds all other progenitor channels between $\sim 0.7-4$ Gyr, and these systems are enough to account for the Galactic SN Ia rate, with a calculated Galactic rate of $\sim 2.6\times10^{-3}$ SN Ia yr^{-1}. For comparison, the DDS Galactic rate is $\sim 2\times10^{-3}$ SN Ia yr^{-1} [see 11, section 4 for discussion of Galactic rate calculation]. Both of these values are within the Galactic rate estimate from Cappellaro et al. [8] of $4\pm2\times10^{-3}$ SN Ia yr^{-1} [see also 31, for a modern SN rate calculation in the local Universe].

TABLE 1. Rates of SNe Ia (SNuM) following a starburst at t=0.

Time	**Rate**
DDS	
0.1 Gyr	2.0×10^{-1}
0.5 Gyr	1.6×10^{-1}
1 Gyr	8.0×10^{-2}
3 Gyr	2.5×10^{-2}
5 Gyr	1.2×10^{-2}
10 Gyr	$\sim 5 \times 10^{-3}$
SDS	
0.1 Gyr	0
0.5 Gyr	$\sim 10^{-3}$
1 Gyr	1.5×10^{-3}
3 Gyr	2.0×10^{-3}
5 Gyr	$\sim 1 \times 10^{-3}$
10 Gyr	$\leq 10^{-3}$
Helium donor ($M_{\rm Ch}$)	
0.1 Gyr	$\sim 3 \times 10^{-3}$
0.5 Gyr	2.2×10^{-2}
1 Gyr	8.0×10^{-3}
3 Gyr	$< 10^{-3}$
5 Gyr	$\leq 10^{-4}$
10 Gyr	~ 0
sub-Chandrasekhar	
0.1 Gyr	$\sim 1 \times 10^{-1}$
0.5 Gyr	$\sim 10^{-3}$
1 Gyr	3.3×10^{-1}
3 Gyr	4.0×10^{-2}
5 Gyr	1.4×10^{-2}
10 Gyr	$\sim 4 \times 10^{-3}$

DISCUSSION

Hydrodynamic simulations of sub-Chandrasekhar mass SNe Ia exhibit observational features which are characteristically similar to those of SNe Ia [23, 24]. Motivated by these findings, as well as population synthesis rate estimates, we have investigated sub-Chandrasekhar mass SN Ia formation channels and have calculated and presented the DTDs and rates of their progenitors.

Within the framework of our adopted model, we find that only the DDS and sub-Chandrasekhar mass channels can potentially explain the observed rates of SNe Ia. However, while the predicted rates of the DDS are not in conflict with observations, these systems are theoretically expected to produce events which lead to AIC. If this is the case, the Galactic AIC rate from this AIC evolutionary (WD merger) channel alone would be as high as $\sim 10^{-3}$ per year. An absence of DDS progenitors from the SN Ia DTD would leave the sub-Chandrasekhar mass model as the only evolutionary scenario able to produce a high enough rate of SNe Ia, as well as a bimodal DTD. However, if one can say for certain that AICs which are formed from the merger of CO WDs produce very neutron-rich ejecta[1], then this provides a potentially strong constraint on the outcome of these mergers – namely that a non-negligible fraction of SNe Ia must be formed through the DDS channel. Maoz & Badenes [3] find that about half of SNe Ia explode within

[1] Yungelson & Livio [10] predicted a Galactic AIC rate of $\sim 10^{-6} - 10^{-4}$ yr^{-1} from population synthesis, though note that this rate does not include mergers of CO-CO WDs. A Galactic rate of $\sim 10^{-4}$ AIC yr^{-1} is the upper limit estimate derived from solar system abundances of neutron-rich isotopes, which are expected to be produced in AICs [32, 33, 34].

330 Myr of star formation, with a significant fraction occurring within 1 Gyr of star formation. If both the DDS and sub-Chandrasekhar mass channels contribute to SNe Ia at short delay times, this could potentially explain both the bimodality in the observed DTD, as well as increase the predicted number of prompt SNe Ia (see Fig. 1).

The sub-Chandrasekhar model is the first model which demonstrates both a sufficient number of SNe Ia events to account for all (or at least some substantial fraction) of SNe Ia, as well as *two distinct evolutionary channels with their own characteristic delay times*: A prompt ($<$ 500 Myr) helium-star channel originating from binaries with more massive secondaries, and a more delayed ($>$ 500 Myr) double WD channel originating from AM CVn-like progenitor binaries with lower mass. Considering the recent observational studies which have found evidence for such a DTD [3, 4, 35], further theoretical investigation of the sub-Chandrasekhar mass SN Ia channel is now strongly warranted.

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