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The effect of helium accretion efficiency on rates of Type Ia supernovae: double-detonations in accreting binaries

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ABSTRACT

The double-detonation explosion scenario of Type Ia supernovae has gained increased support from the SN Ia community as a viable progenitor model, making it a promising candidate alongside the well-known single degenerate and double degenerate scenarios. We present delay times of double-detonation SNe, in which a sub-Chandrasekhar mass carbon-oxygen white dwarf accretes non-dynamically from a helium-rich companion. One of the main uncertainties in quantifying SN rates from double-detonations is the (assumed) retention efficiency of He-rich matter. Therefore, we implement a new prescription for the treatment of accretion/accumulation of He-rich matter on white dwarfs. In addition, we test how the results change depending on which criteria are assumed to lead to a detonation in the helium shell. In comparing the results to our standard case (Ruiter et al. 2011), we find that regardless of the adopted He accretion prescription, the SN rates are reduced by only ~ 25 per cent if low-mass He shells ($\lesssim 0.05\,\mathrm{M}_\odot$) are sufficient to trigger the detonations. If more massive ($0.1\,\mathrm{M}_\odot$) shells are needed, the rates decrease by 85 per cent and the delay time distribution is significantly changed in the new accretion model – only SNe with prompt ($< 500\,\mathrm{Myr}$) delay times are produced. Since theoretical arguments favour low-mass He shells for normal double-detonation SNe, we conclude that the rates from double-detonations are likely to be high, and should not critically depend on the adopted prescription for accretion of He.

Key words: binaries : close — supernovae — white dwarfs

1 INTRODUCTION

It is a widely-accepted view that Type Ia supernovae (SNe Ia) arise from the thermonuclear explosion of a white dwarf (WD) star (see Hillebrandt et al. 2013). Until a few years ago, the favoured progenitor scenario that was said to lead to SNe Ia was the single degenerate scenario (SD), by which a carbon-oxygen (CO) WD accretes from a (probably hydrogen-rich) non-degenerate companion star, until the WD's central density becomes sufficiently high to ignite carbon. Such high densities are likely achieved for CO WDs that approach the Chandrasekhar mass limit ($\sim 1.4\ \mathrm{M}_\odot$). The other well-known progenitor scenario is the double degenerate (DD) scenario, in which two WDs merge. Previously, it was expected that the primary WD had to achieve near-Chandrasekhar mass before explosion, though it is becoming more clear that this is not necessarily the case: Recent work has shown that sub-Chandrasekhar mass WD explosions are successful in synthesizing ^{56}Ni in sufficient amounts during violent mergers (see e.g. Pakmor et al. 2012).

A third progenitor scenario that has recently gained more positive attention is the double-detonation scenario, in which a detonation is triggered off-centre in a sub-Chandrasekhar mass WD following an initial detonation in a He layer (or 'shell') that has been accumulated on the WD surface (e.g. Livne 1990; Iben & Tutukov 1991; Woosley & Weaver 1994; Livne & Arnett 1995; Fink et al. 2010; Townsley et al. 2012; Moore et al. 2013). Early studies indicated that this 'classic' double-detonation scenario – where a CO WD accumulates mass from a He-rich companion that is stably filling its Roche lobe[1] – was not a promising SN Ia scenario

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[1] Note that double-detonation explosion mechanisms may also be encountered during mergers that proceed on dynamical timescales (Guillochon et al. 2010; Pakmor et al. 2013; Shen et al. 2013). Throughout

since theoretical spectra and lightcurves did not match those of normal SNe Ia (Hoeflich & Khokhlov 1996; Nugent et al. 1997; García-Senz et al. 1999). However, more recent work has shown that lightcurves, spectra and nucleosynthesis from these explosions may compare relatively well with observational data (Kromer et al. 2010; Woosley & Kasen 2011). The main difference between the recent studies and those performed in the 1990s is the realization that a thick ($\sim$0.2 $\mathrm{M}_{\odot}$) He shell is likely not needed for a detonation. With a lower He shell mass, there is no longer a significant over-production of Fe-peak elements at high velocities, which brings model spectra into better agreement with SN Ia observations.

As discussed in Ruiter et al. (2011), the double-detonation model for SNe Ia is attractive for several reasons:

- The lack of hydrogen in SN Ia spectra is a natural result.
- The range in exploding (primary WD) mass provides a simple, physical parameter that accounts for the observed variety among SN Ia peak-brightness and lightcurve width.
- Model spectra and lightcurves show potential for looking as good as DD and SD model spectra/lightcurves when compared with observational data.
- Predicted rates are high enough to possibly explain a large fraction of SNe Ia, and the delay time distribution (DTD) compares well with observational data (Ruiter et al. 2011).

These criteria are also fulfilled by the violent white dwarf merger scenario (Pakmor et al. 2012). Nonetheless, given the diversity of SNe Ia, it is likely that more than one progenitor channel contributes to the observed population. Thus, it is clear that further exploration of the double-detonation scenario is important. In this paper, we re-examine the fourth of these bullet points. One factor that is expected to strongly affect rates of double-detonations is the retention efficiency of He material on WD accretors, and so we test the assumptions involved in the physical treatment of this process with new input physics. Piersanti et al. (2013) (hereafter P13) concluded that the Ruiter et al. (2011) rates of double-detonation SNe Ia – whose progenitors were WDs with total masses > 0.9 $\mathrm{M}_{\odot}$ – are likely overestimated. When taking into account the thermal response of the He-accreting WD in long-term evolutionary calculations, P13 found it unlikely that the CO WD would grow substantially in mass during high mass transfer rates, in contrast to Kato & Hachisu (2004) (hereafter KH04). To test this, we have implemented a new prescription for the retention efficiency of He-rich matter into our binary evolution calculations that is based on the study of P13. Another factor to consider, as it likely affects the explosion masses, is the assumed criteria leading to a detonation in the He shell. We test different conditions for this as well.

2 MODELLING: OLD VS. NEW INPUT PHYSICS

Despite being an integral piece of physics to the understanding of SNe Ia and interacting binaries in general, our theoretical picture of retention efficiency in mass-transferring binaries remains incomplete.[2] In order to quantify the total number (and relative frequency) of SNe Ia that may arise from the proposed formation channels, we must turn to binary population synthesis (BPS) methods (see Toonen et al. 2013, for a comprehensive BPS comparison study). Various prescriptions for the treatment of mass accretion have been adopted in different BPS codes, and the different parametrizations/prescriptions are one of the factors contributing to the variability in SN Ia rate predictions among different groups (see Mennekens et al. 2010; Nelemans et al. 2013; Bours et al. 2013).

Ruiter et al. (2011) adopted the He accretion prescription of Kato & Hachisu (1999, 2004) and assumed that a He shell mass of 0.1 $\mathrm{M}_{\odot}$ was needed to trigger a double-detonation (see also Belczynski et al. 2005). In addition, Ruiter et al. (2011) assumed a double-detonation SN Ia explosion only occurs if the total WD mass (CO 'core' $+0.1$ $\mathrm{M}_{\odot}$ 'shell') $\geqslant 0.9$ $\mathrm{M}_{\odot}$. In that work, rates and delay times of SN Ia from several evolutionary channels were calculated with the BPS code `StarTrack` (Belczynski et al. 2002, 2008) with three different parametrizations for the common envelope (CE) phase. For our standard model, the values $\alpha_{\mathrm{CE}} = 1$ and $\lambda = 1$ were adopted (see Ruiter et al. 2011, sect. 3). Since our standard model yielded the highest rate of SNe Ia, in particular for double-detonation SNe Ia (Ruiter et al. (2011), table 1), we use those results as a benchmark for comparison to the current study.

In an accreting binary system, some fraction of material lost from the donor remains bound to the accretor. The value of this fraction, η, and exactly how it evolves during binary evolution is uncertain. Nevertheless, if one adopts a recipe prescribing how the amount of retained matter depends on e.g. the donor mass transfer rate and the mass of the accreting WD, this can be incorporated into BPS studies and used to understand how assumptions about η influence predicted properties of a binary population. Since larger values of η will generally result in larger CO WD masses, testing different treatments for the retention of He-rich matter derived from different research groups is critical in determining uncertainties in the rates, delay times and physical properties of SN Ia progenitors. This is true in particular for double-detonation SNe Ia, but it also has an effect on the DD and HeR (He-rich Chandrasekhar mass WD) scenarios. The implications for these other progenitors will be discussed in a forthcoming paper (Ruiter et al. in prep.); for the current study we focus on double-detonations.

The response of the accreting WD upon receiving mass depends on the WD mass and the rate at which mass is being transferred from the donor (e.g. Moll & Woosley 2013). For very high mass transfer rates ($\sim 10^{-5}$ $\mathrm{M}_{\odot}\mathrm{yr}^{-1}$, when mass transfer first begins from a He to a CO WD)[3], the retention efficiency can vary in a wide range. When the rate of transfer is higher than the rate of burning, the transferred He can form a 'red giant-like envelope' on the WD surface (see Nomoto 1982), and a substantial amount of material may be lost. As the mass transfer proceeds at lower rate, but is still fairly high ($\sim$ few $\times 10^{-6}$ $\mathrm{M}_{\odot}\mathrm{yr}^{-1}$), more of the transferred material is burned and adds to the WD's mass, and eventually a regime of stable burning can be achieved (Iben & Tutukov 1989, IT89). As the orbit increases and the mass transfer rate drops further, burning becomes unstable as the binary enters a flash cycle where only some of the transferred matter is accreted, the rest being lost from the binary (KH04). Lastly, when/if the mass transfer rate drops to a sufficiently low value (typically $\dot{M} < 10^{-7}$ $\mathrm{M}_{\odot}\mathrm{yr}^{-1}$), material accumulates on the WD surface efficiently, but tempera-

this paper, *we do not discuss mergers*, and we refer to 'double-detonation' to mean systems in which the companion star is filling its Roche lobe and transferring matter to the primary WD on a non-dynamical timescale.

[2] Although it is important to also consider the effect of retention efficiency of hydrogen-rich material on SN Ia progenitors in general (Idan et al. 2013), we do not explore that here. For double-detonation SN Ia candidates, stable mass transfer phases involving hydrogen-rich donors are less important.

[3] Our donor stars consist of He-rich WDs and low-mass He-burning stars. Initial mass transfer rates from these 'main sequence He stars' are typically low: $\sim$few $\times 10^{-8}$ $\mathrm{M}_{\odot}\mathrm{yr}^{-1}$.

tures are not high enough for He burning. If this He shell reaches a critical mass, the physical conditions in the (degenerate) He layer may be sufficient to trigger a He flash that evolves as a detonation (e.g. Taam 1980). This first detonation is then likely to trigger a second detonation closer to the WD centre (Fink et al. 2010; Shen & Bildsten 2013; Moll & Woosley 2013).

Previously-adopted (old) He accretion prescription: For accretion of He-rich matter on WDs, the adopted prescription (e.g. used in Ruiter et al. 2011) is based on detailed He flash calculations from KH04. They found that for He accretion rates $\gtrsim 10^{-6}$ $M_\odot$ yr^{-1}, η approaches or is equal to 1 (see their fig. 2), whereas η will have a range of values for lower accretion rates. We group the accretion stages described in Sect. 2 into four 'regimes' to summarise how the input physics is treated in our binary evolution calculations (see KH04 for formulae):
i) *accretion at high* $\dot{M}$: stable He burning is assumed ($\eta = 1$)
ii) *steady accretion regime*: stable He burning ($\eta = 1$)
iii) *helium flash regime*: unstable He burning ($0 < \eta < 1$; adopted eq. 1-6 from KH04)
iv) *steady accumulation/double-detonation regime*: accumulation of He 'shell' ($\eta = 1$, no burning).
The build-up of the He shell that is needed for a double-detonation to occur is only possible if the binary is evolving in regime iv. We note that for the KH04 model, regimes i and ii are identical in terms of efficiency. While we restrict all WD-accretion to be Eddington-limited, assuming $\eta = 1$ for high mass transfer rates is likely to over-estimate the amount of mass gained, as mentioned in P13.

Newly-adopted He accretion prescription: We incorporate an accretion scheme that is based on P13 ($\dot{M}$ vs. $M_{\rm WD}$, their fig. 1). Since P13 do not include detailed information about accretion efficiencies or formulae, we construct a model that assumes the retention of He-rich matter follows the trends illustrated in P13 until a more precise treatment becomes available (L. Piersanti, private communication 2012). Such a model, though simple, is an important step towards quantifying the effect that different physical treatments for accretion have on SN Ia rates and exploding WD mass. We fit the boundaries ($\dot{M}_{\rm crit}$) that separate retention regimes shown in their fig. 1 using $\dot{M}_{\rm crit} = a{\rm e}^{bM}$, where a and b are the fitted coefficients and M is the mass of the accretor (see Table 1). We adopt the following retention regimes:
i) *accretion at high* $\dot{M}$*, so-called 'red giant' configuration*: We assume $\eta =$min(1.0, $\dot{M}_{\rm crit}/\dot{M}$)
ii) *steady accretion and mild flash regime*: we assume full efficiency for burning (steady accretion) or accumulation (mild flashes), thus $\eta = 1$ (see P13)
iii) *strong flash regime*: we adopt $\eta = 0.\overline{3}$ based on P13 who state that a range between $0.11 < \eta < 0.77$ is feasible
iv) *steady accumulation/double-detonation regime*: accumulation of He 'shell' ($\eta = 1$, no burning).

We assume that a double-detonation thermonuclear explosion will ensue if a shell of accumulated (unburned) He reaches a critical value. In one case we assume a value of $0.1 M_\odot$ as was adopted in Ruiter et al. (2011). We also explore the case where a double-detonation is presumed to occur with a He shell mass of $0.05\ M_\odot$. This is a more reasonable assumption given recent studies of He accretion with 1D hydrodynamical simulations in the context of double-detonations (Woosley & Kasen 2011, see also Moore et al. 2013). However, this critical shell mass likely depends on the WD mass (see e.g. Bildsten et al. 2007), with shell mass being inversely proportional to WD 'core mass'. Therefore, in addition to our constant shell mass models, we adopt a model that uses CO WD core mass dependent shells. For this, we consider three different shell

Table 1. Coefficients for the 7 exponential functions that we fit using fig. 1 of P13 as a guide (see text). The table data shown represent the critical limits between two adjacent regimes. Note that $\eta = 1$ is assumed for CO WD accretors with small initial masses ($< 0.61\ M_\odot$, see also KH04).

regime	WD mass [$M_\odot$]	a [$M_\odot$ yr^{-1}]	b [$M_\odot$$^{-1}$]
i-ii	0.61 - 0.85	1.95964598e-08	4.93404225
i-ii	0.85 - 1.05	3.19735998e-08	4.35598835
i-ii	1.05 - 1.4	4.30115846e-07	1.88390002
ii-iii	0.61 - 1.025	1.93277991e-09	5.20188685
ii-iii	1.025 - 1.4	2.65362072e-08	2.66212858
iii-iv	0.61 - 0.8	9.67049947e-10	4.29852144
iii-iv	0.8 - 1.0	9.28070998e-09	1.45637761
iii-iv	1.0 - 1.4	4.0e-8	0

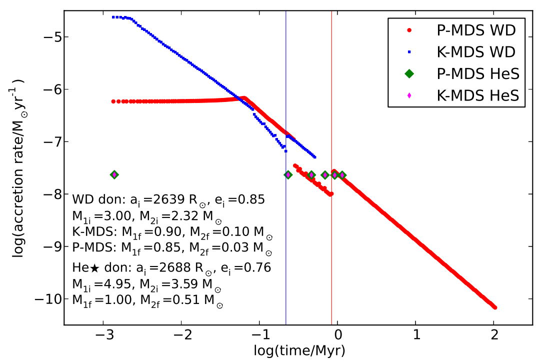

Figure 1. Mass accretion rate as a function of time relative to start of mass transfer for double-detonation progenitors in the K-MDS and P-MDS models. Breaks in the data showing the WD donor systems represent transitions between regimes: e.g. from regime ii ($\eta = 1$) to regime iii ($\eta < 1$) to regime iv ($\eta = 1$). The relative times at which regime iv is achieved are indicated by vertical lines for the WD donor case (blue; K-MDS and red; P-MDS). The system with a helium star donor (HeS) reaches regime iv immediately when mass transfer begins for both accretion models. ZAMS parameters ($_{\rm i}$) and masses at explosion ($_{\rm f}$) are shown on the figure.

criteria, since the exact conditions that will lead to a He shell detonation at low $\dot{M}$ are not currently well-constrained. The first two cases are based on eq. 11a from IT89, which was originally constructed to estimate ignition shell masses for WDs accreting at *constant* $\dot{M}$. For the first of these we use the $\dot{M}$ value the binary had once it crossed into regime iv, and for the second we use the *instantaneous* value of $\dot{M}$. We label these ignition masses $M_{\rm ITc}$ and $M_{\rm ITi}$, respectively. We additionally consider minimum shell masses for dynamical burning $M_{\rm SBd}$ from Shen & Bildsten (2009) (their fig. 5, lower curve). Achieving such a minimum shell mass does not necessarily lead to shell ignition, though in theory, these masses represent a lower limit on the detonation shell mass. If a binary evolving in regime iv accumulates a He shell exceeding any of the three aforementioned shell masses, it is assumed to undergo a double-detonation. By considering three estimates for the critical shell mass and assuming that explosion occurs as soon as the smallest one is achieved, we provide an upper limit on rates of double-detonations within this mass-dependent shell framework. As in Ruiter et al. (2011), we additionally assume that a SN Ia only occurs for systems where the primary WD has a *total* mass $\geqslant 0.9$ $M_\odot$. Our six models are labelled as follows: KH04 prescription with 0.1 and 0.05 $M_\odot$ shell, respectively: K0.1, K0.05; P13 prescription with 0.1 and 0.05 $M_\odot$ shell, respectively: P0.1, P0.05; core mass dependent shell masses: K-MDS, P-MDS, respectively.

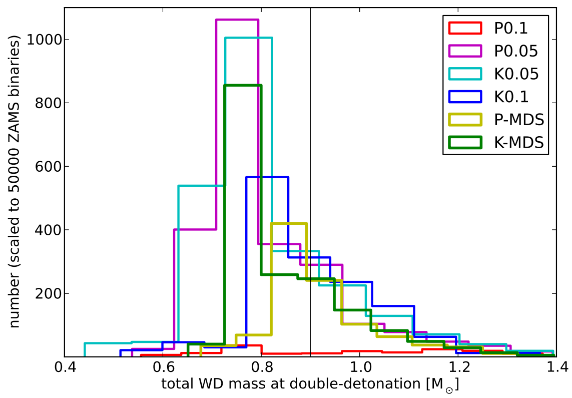

Figure 2. Mass distribution of primary WDs that are predicted to undergo double-detonations in `StarTrack` for six models. We show the whole mass range, though only the systems to the right of the vertical black line are likely to explode as SNe Ia (see text).

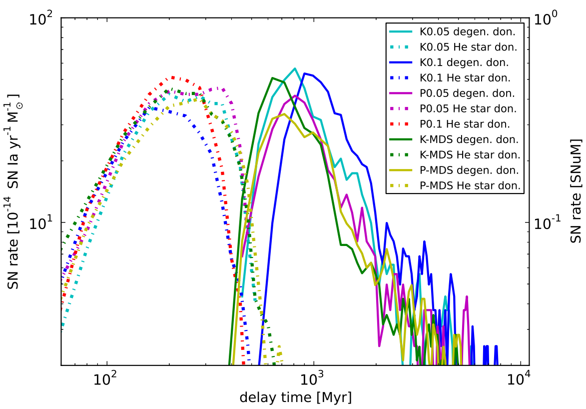

Figure 3. Rates as a function of delay time from double-detonations assuming a binary fraction of 70 per cent. Only systems that have primary WD masses $\geqslant 0.9$ $\mathrm{M}_{\odot}$ are shown (see text). The P0.1 model produces only prompt SNe Ia (delay times < 500 Myr).

In Fig 1 we show examples that lead to a double-detonation in the K-MDS and the P-MDS models: a WD donor and a He star donor. Both systems undergo two common envelopes followed by a stable mass transfer phase (plotted). The K-MDS WD system initially accretes with $\eta = 1$, while the P-MDS WD system initially has $\eta = 0.015$ (regime i). The K-MDS WD system explodes with core and shell masses 0.871 and 0.024 $\mathrm{M}_{\odot}$, respectively, when M_{ITc} is achieved. The M_{ITi} and M_{SBd} shell masses are both within a factor of 2: 0.039 and 0.042 $\mathrm{M}_{\odot}$, respectively. The P-MDS WD system explodes later with core and shell masses 0.781 and 0.066 $\mathrm{M}_{\odot}$, respectively, when M_{SBd} is achieved. The M_{ITc} mass is very similar: 0.070 $\mathrm{M}_{\odot}$, though M_{ITi} is unrealistically high: $\sim$2 $\mathrm{M}_{\odot}$. This is a reflection of the fact that eq. 11a from IT89 is a poor estimator of ignition shell mass for lower WD core masses that require long timescales (and therefore large changes in $\dot{M}$) to accumulate a sufficient amount of He. The He-star system undergoes a brief phase of mass transfer with identical behaviour for both models, entering regime iv immediately upon mass transfer. At explosion the core and shell masses are 0.966 and 0.032 $\mathrm{M}_{\odot}$, respectively. The shell mass lies in between the dynamical mass M_{SBd} (0.028), and the ignition masses M_{ITc} (0.033) and M_{ITi} (0.034) $\mathrm{M}_{\odot}$, respectively.

Table 2. Second column shows relative occurrence rates over a Hubble time, last three columns show donor types (by per cent) of double-detonation SNe Ia. We only list the statistics for events where the total exploding WD mass is $\geqslant 0.9$ $\mathrm{M}_{\odot}$.

model	Rel. frac.	He WD	Hyb WD	He-star
K0.1	1	79	10	11
K0.05	0.92	74	9	17
P0.1	0.15	0	1	99
P0.05	0.79	67	10	23
K-MDS	0.76	64	12	24
P-MDS	0.73	68	8	24

3 RESULTS

In Fig. 2 we show the mass distribution of WDs that accumulate the critical shell mass for a double-detonation as predicted by our BPS calculations. For systems with constant shell mass, the 0.05 $\mathrm{M}_{\odot}$ shell models produce a larger number of events compared to the 0.1 $\mathrm{M}_{\odot}$ shell models that require twice as much He. Since we terminate our calculation if the donor star mass drops < 0.01 $\mathrm{M}_{\odot}$, binaries with extremely low-mass donors are excluded from our results. For the core mass dependent shell models, lower mass WDs must accumulate somewhat larger shell masses. Consequently, the total WD mass at explosion is systematically higher for low mass systems (and slightly lower for high mass systems) in the MDS models. The peak in K-MDS is noticeably higher than the peak in P-MDS due to the assumption of fully efficient accretion in regime i in KH04; the P-MDS donor often runs out of mass before any ignition criteria are reached, and instead the binary evolves as a typical AM CVn system. The outcome of double-detonations in low-mass CO WDs was explored in Sim et al. (2012). That work has shown that fast transient events can arise from such systems, with the amount of Fe-group and intermediate-mass elements synthesized depending on the exact nature of the explosion mechanism. In any case, the lightcurves will be fainter and faster-declining than normal SNe Ia. Here, we are interested in candidates for SNe Ia of normal brightness. For this reason, we assume – as in Ruiter et al. (2011) – that a double-detonation SN Ia only arises in primary WDs of total mass $\geqslant 0.9$ $\mathrm{M}_{\odot}$. Such an explosion is likely to yield a ^{56}Ni mass that is around the lower limit of observationally-inferred ^{56}Ni masses (Sim et al. 2010; Ruiter et al. 2013). Though the core and shell masses will have an effect on the resulting spectral signature, to first order the total mass of ^{56}Ni synthesized in a double-detonation is fixed by the *total* mass of the primary WD.

The main difference between the two different accretion schemes (KH04 and P13) is that KH04 is more favourable for building up the mass of the WD, specifically within regime i. In addition, the η values achieved during regime iii are generally higher in the KH04 models. Consequently, these systems enter the double-detonation regime with more massive binary components.

We find that the DTD of double-detonation SNe Ia is significantly altered from that of Ruiter et al. (2011) when the P13 retention efficiency is adopted and the WD is required to accumulate a 0.1 $\mathrm{M}_{\odot}$ He shell (see Fig. 3). The reason has to do with the nature of the progenitors: they all involve relatively massive donors – no He WDs (see Table 2). The only double-detonation SN Ia systems found in the P0.1 model are those with either He-burning star donors or (rarely) ‘hybrid’ WD donors that consist of a CO-core and a He-rich mantle. During mass transfer, more matter is lost from the binary in the P0.1 model and the He WD donors run out of matter before the critical shell mass is reached. Thus, He WD + CO

WD binaries cannot make double-detonation progenitors in P0.1. This is the reason for the significant decrease (by a factor of $\sim$7) in the rates of double-detonation systems in this model compared to Ruiter et al. (2011) (see Table 2, where the K0.1 model is the one comparable to the standard results of Ruiter et al. 2011). However, this decrease is mitigated if we allow for double-detonations in which a smaller amount of accumulated He is required, as is the case for the P0.05, K0.05, P-MDS and K-MDS models. For the MDS models, if each ignition shell criterion is considered separately (rather than choosing the lowest mass), the rates for P13 do not change for $M_{\rm ITc}$ or $M_{\rm SBd}$, though they drop by 60 per cent for $M_{\rm ITi}$. For KH04 the rates do not change for $M_{\rm ITc}$, they drop by 20 per cent for $M_{\rm SBd}$, and they drop by 40 per cent for $M_{\rm ITi}$.

4 SUMMARY

We have compared rates of double-detonation SNe Ia arising from sub-Chandrasekhar mass CO WDs accreting He-rich matter on non-dynamical timescales for two prescriptions for He retention efficiency. In addition, we have tested the prescriptions assuming different critical values for accumulated He shell mass above which a double-detonation is presumed to occur: constant shell masses as well as CO WD core mass dependent shell masses.

If a thick ($0.1\ {\rm M}_{\odot}$) shell of He is a necessary condition to achieve a double-detonation SN Ia, then most events will have He-star donors and should be found among young stellar populations if our newly-adopted retention efficiency prescription (P13) is assumed. This finding is in stark contrast to the results of Ruiter et al. (2011), who found that most double-detonations will arise from CO WDs accreting from He WD donors. If only thin He shells are required, then it will be difficult to disentangle progenitor evolution based on delay time alone, regardless of the assumed mass-retention model. However, the assumed mass-retention model should not significantly affect the expected rates.

In contrast to older models that assumed thick shells, recent models indicate that thin He shells produce observables that agree fairly well with observations (e.g. Kromer et al. 2010; Woosley & Kasen 2011). This is particularly true for double-detonations leading to 'normal' SNe Ia that call for fairly massive CO WDs ($\gtrsim$1 ${\rm M}_{\odot}$, see also Piro et al. 2014) and thus likely require small He shells. Understanding the mass dependence of the detonating shell is a complex problem. Here, we have explored a range of possibilities to estimate the WD explosion mass (and rate) by including detonation and ignition shell calculations based on core mass and accretion rate. Such models (K-MDS and P-MDS) are more realistic than assuming a constant shell mass. However, it turns out that the assumed ignition criterion is, to first order, not of crucial importance if the critical shell mass is low ($\lesssim$0.05 ${\rm M}_{\odot}$): in this case the total rate of double-detonations remains high.

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