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Reconciling ^{56}Ni production in Type Ia supernovae with double degenerate scenarios

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ABSTRACT

We combine the observed distribution of Type Ia supernova (SN Ia) ^{56}Ni yields with the results of sub-Chandrasekhar detonation and direct collision calculations to estimate what mass white dwarfs (WDs) should be exploding for each scenario. For collisions, the average exploding WD mass must be peaked at $\approx$0.75 M$_\odot$, significantly higher than the average field WD mass of $\approx$0.55–0.60 M$_\odot$. Thus, if collisions produce most SNe Ia, then a mechanism must exist that favours higher mass WDs. On the other hand, in old stellar populations, collisions would naturally result in low-luminosity SNe Ia, and we suggest these may be related to 1991bg-like events. For sub-Chandrasekhar detonations, the average exploding WD mass must be peaked at $\approx$1.1 M$_\odot$. This is similar to the average total mass in WD–WD binaries, but it is not clear whether double degenerate mergers would synthesize sufficient ^{56}Ni to match observed yields. If not, then actual $\approx$1.1 M$_\odot$ WDs would be needed for sub-Chandrasekhar detonations. Since such high-mass WDs are produced relatively quickly in comparison to the age of SN Ia environments, this would require either accretion on to lower mass WDs prior to ignition or a long time-scale between formation of the $\approx$1.1 M$_\odot$ WD and ignition.

Key words: nuclear reactions, nucleosynthesis, abundances – supernovae: general – white dwarfs.

1 INTRODUCTION

The use of Type Ia supernovae (SNe Ia) as precision probes of cosmology (e.g. Riess et al. 1998; Perlmutter et al. 1999) will ultimately be limited by systematic uncertainties. Understanding and minimizing these uncertainties should be advanced by having a complete physical understanding of the underlying mechanism behind the explosion. Thus, one of the consequences of the focus on SNe Ia as cosmological distance indicators has been to emphasize the enormous theoretical uncertainties that remain about these events.

It is generally accepted that SNe Ia result from unstable thermonuclear ignition of degenerate matter (Hoyle & Fowler 1960) in a C/O white dwarf (WD), but, frustratingly, the specific progenitor systems have not yet been identified. The three main candidates are (1) stable accretion from a non-degenerate binary companion until the Chandrasekhar limit is reached (single degenerates; Whelan & Iben 1973), (2) the merger of two C/O WDs (double degenerates; Iben & Tutukov 1984; Webbink 1984) or (3) accretion and detonation of a helium shell on a C/O WD that leads to a prompt detonation of the core (double detonations; Woosley & Weaver 1994; Livne & Arnett 1995). An important outstanding problem is to understand how these scenarios contribute to the SNe Ia we observe, and whether any one channel is dominant.

In recent years, the double degenerate mechanism has been increasingly at the centre of attention. Observationally, there are arguments in favour of this scenario from the non-detection of a companion in pre-explosion imaging of nearby SNe Ia (Li et al. 2011b), the lack of radio emission from SNe Ia (Hancock, Gaensler & Murphy 2011; Horesh et al. 2012), the lack of hydrogen emission in nebular spectra of SNe Ia (Leonard 2007; Shappee et al. 2013a), a lack of a signature of ejecta interaction with a companion (Kasen 2010; Hayden et al. 2010; Bloom et al. 2012) and the missing companions in SNe Ia remnants (Edwards, Pagnotta & Schaefer 2012; Schaefer & Pagnotta 2012, also see the studies by Kerzendorf et al. 2012, 2013a,b) even though they should be superluminous (Shappee, Kochanek & Stanek 2013b). In addition, the delay time distribution of SNe Ia follows a power-law distribution as is expected for double degenerates (Maoz, Sharon & Gal-Yam 2010; Graur et al. 2011; Barbary et al. 2012; Sand et al. 2012). Potential problems with matching the rate of SNe Ia with double degenerate mergers may be alleviated if the mergers are in sub-Chandrasekhar WD–WD binaries (van Kerkwijk, Chang & Justham 2010; Badenes & Maoz 2012).

On the theoretical side, double degenerate scenarios have historically been disfavoured because accretion after tidal disruption triggers burning that turns the C/O WD into a O/Ne WD

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(Nomoto & Iben 1985; Saio & Nomoto 1998), which then collapses to a neutron star due to electron captures (Nomoto & Kondo 1991). This problem remains even with more detailed treatments of the long-term evolution of the merger remnant (Shen et al. 2012). More recently though, the double degenerate scenario has been revitalized by new simulations which indicate that ignition may be triggered by a detonation in an accretion stream (Guillochon et al. 2010; Dan et al. 2012) or in 'violent mergers' involving massive WDs (Pakmor et al. 2012). WDs may also explode in direct collisions (Rosswog et al. 2009; Raskin et al. 2010; Hamers et al. 2013; Kushnir et al. 2013), which would be another way for double degenerates to give rise to SNe Ia. While this scenario may have been viewed as unlikely only a few years ago, recent studies show that triple systems are more common (Raghavan et al. 2010) than previously thought, and that the Kozai mechanism both greatly accelerates binary mergers (Thompson 2011) and drives direct collisions (Katz & Dong 2012) in such systems.

With this increased focus on double degenerate scenarios, the time is ripe to make better comparisons to observed and theoretical populations of WD binaries. In this work, we investigate this problem using the following strategy. First, the observed luminosity distribution of SNe Ia implies a corresponding distribution of radioactive ^{56}Ni synthesized, which we present in Section 2. Next, the relation between WD mass and ^{56}Ni yield for a given explosion scenario means that certain mass WDs much be exploding to produce the SNe Ia that we observe. In Section 3, we perform this exercise and find that sub-Chandrasekhar detonation models and collision calculations favour the explosion of $\approx$1.1 and $\approx$0.75 $M_\odot$ WDs, respectively. The implications of this conclusion are then investigated with comparisons to the mass distribution of field WDs and Monte Carlo calculations of WD–WD binaries in Section 4. We conclude in Section 5 with a summary of our results and a discussion of future explorations of this problem.

2 THE OBSERVED ^{56}NI DISTRIBUTION

We begin by investigating the range of ^{56}Ni masses, M_{56}, produced in SNe Ia. To do this, we focus on the volume-limited sample of 74 SNe Ia within 80 Mpc from the Lick Observatory Supernova Search (LOSS; Li et al. 2011a). The sample is estimated to be 98 per cent complete due to the high peak luminosity of these SNe. There may be some bias because LOSS targets specific galaxies rather than broadly surveying the sky. For example, the sample is mostly composed of normal SNe Ia, without any super-Chandrasekhar events (e.g. SN 2003fg; Howell et al. 2006) possibly because these tend to be associated with low-metallicity dwarf galaxies (Khan et al. 2011) that are not a focus of the survey. Since the rate of super-Chandrasekhar events is rather overall low ($\sim$2 per cent; Scalzo et al. 2012), this probably does not impact the distribution substantially. Another possible limitation is that the galaxy sample is incomplete starting for galaxies with K-band luminosities below $\sim 4 \times 10^{10}\,L_\odot$. This corresponds to the targeted galaxies accounting for $\sim$45 per cent of the total stellar light that is accessible to the survey (Leaman et al. 2011). Aside from the super-Chandrasekhar SNe Ia, this is not known to provide any other bias.

By combining modelling of the late-time nebular spectra of SNe Ia with measurements of their bolometric peak, Stritzinger et al. (2006) demonstrated that $\Delta m_{15}(B)$ (the B-band magnitude change 15 d post-peak) is a reliable indicator of the ^{56}Ni yield. This has the additional advantage that it is relatively insensitive to extinction corrections in comparison to other possible ^{56}Ni indicators.[1] Therefore, to infer the ^{56}Ni mass produced in each SN Ia, we use the decline rate–nickel mass relation presented in Mazzali et al. (2007),

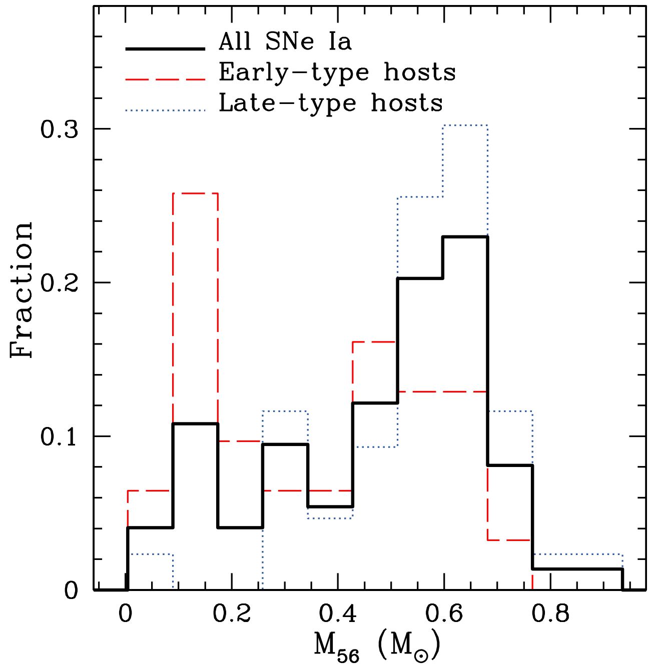

Figure 1. Histograms showing the fraction of SNe Ia that produce different amounts of ^{56}Ni found by combining the volume-limited LOSS sample of SNe Ia (Li et al. 2011a) with the decline rate–nickel mass relation (Mazzali et al. 2007).

$$M_{56}/M_\odot = 1.34 - 0.67\Delta m_{15}(B), \quad (1)$$

which has an rms dispersion of 0.13 $M_\odot$. Unfortunately, $\Delta m_{15}(B)$ is not available directly in Li et al. (2011a), and so we compiled a list of $\Delta m_{15}(B)$ values from a number of other references (Krisciunas et al. 2000, 2004; Modjaz et al. 2001; Hicken et al. 2009; Wang et al. 2009; Ganeshalingam et al. 2010, 2012; Folatelli et al. 2013; Foley et al. 2013). This exercise still left 14 out of the 74 SNe Ia without measured $\Delta m_{15}(B)$ values. Out of these, eight were completely normal SNe Ia (seven of which were in late-type galaxies), and thus, we assume they produce $M_{56} \approx 0.55$–$0.65\,M_\odot$, consistent with all their other properties. This assumption did not change the overall ^{56}Ni distribution we derived appreciably. The other six were all 1991bg-like SNe Ia, all of which were in early-type galaxies. It has been well established that this subluminous class of SNe Ia synthesize a small amount of ^{56}Ni (Sullivan et al. 2011), and thus, we assume that each of these SNe have $M_{56} = 0.1\,M_\odot$, consistent with other members of this class. Our assumptions for these objects, although justified, indeed made a noticeable difference in the derived ^{56}Ni distribution, which we discuss later in this section.

In Fig. 1, we show histograms summarizing this analysis. We compare all SNe Ia (black, solid line) with SNe Ia from early-type host galaxies (red, dashed line) and late-type host galaxies (blue, dotted line). The overall peak is at $M_{56} \approx 0.60\,M_\odot$, as has been well established for typical SNe Ia. It is also well known that SNe Ia are on average brighter in late-type galaxies in comparison

[1] We thank S. Dong for bringing this to our attention, so that we could correct our ^{56}Ni yields from a previous version of this paper.

to early-type galaxies (e.g. Howell et al. 2007), which corresponds to the average SNe Ia in a late-type galaxy producing $\approx 0.13\,\mathrm{M}_\odot$ more ^{56}Ni (Piro & Bildsten 2008). This difference is also apparent in Fig. 1. Because combining both types of hosts provides the best statistics on the M_{56} distribution, we focus on the overall luminosity distribution of all SNe Ia together for most of the remainder of the present study. In the future, similar analysis can and should be applied to SNe Ia with early- and late-type hosts separately.

An additional feature of Fig. 1 that deserves mention is the apparent peak in the ^{56}Ni production at around $M_{56} \approx 0.1\,\mathrm{M}_\odot$, which is especially conspicuous for early-type galaxies. This is due exclusively to the 1991bg-like events. Since we were forced to approximate the ^{56}Ni yield for six of these events, it is prudent to question whether we have introduced this feature with our assumptions. We do not think this is the case. Even if we would have assumed that these events produced $M_{56} \approx 0.2\,\mathrm{M}_\odot$ (as inferred in González-Gaitán et al. 2012), this peak would have been just as prominent. We could have instead split the six events between two bins, roughly centred at 0.1 and $0.2\,\mathrm{M}_\odot$, respectively. This would make the peak somewhat smaller, but it would still clearly appear as a feature in the distribution.

Even though it has long been appreciated that 1991bg-like events are distinct from other SNe Ia in many ways, their contribution to the overall SNe Ia rate in a volume-limited sample is dramatic. Out of 31 SNe Ia in early-type galaxies in the LOSS sample, 10 are 1991bg-like, which is more than 30 per cent.[2] In comparison, only a single 1991bg-like event occurred in a late-type galaxy. Furthermore, the subluminous SN Ia rate is found to be consistent with only being dependent on the galactic mass (as opposed to depending on the star formation rate; González-Gaitán et al. 2011). Clearly an old stellar population is a crucial prerequisite for producing this class of SNe, which is a point we explore further in Section 4.1.

3 PROGENITOR WD MASS DISTRIBUTIONS

Different SNe Ia mechanisms imply different relations between the mass of the exploding WD and the amount of ^{56}Ni synthesized. For this work, we focus on two scenarios for double degenerate explosions as follows.

Sub-Chandrasekhar Detonations. We use the work of Sim et al. (2010), which considers the detonation of sub-Chandrasekhar WDs. They find that they can reproduce the range of M_{56} needed for the observed typical SNe Ia given a relatively narrow spread of WD masses of $M_{\rm WD} \approx 0.97$–$1.15\,\mathrm{M}_\odot$. Although they do not study a specific mechanism for triggering these detonations, such an event could occur in a double detonation following helium accretion from a non-degenerate helium star or a helium WD (Fink et al. 2010) or in a WD–WD merger from a circular orbit (van Kerkwijk et al. 2010). We fit their results with a third-order polynomial, focusing on their models that are equal parts carbon and oxygen,

$$\log_{10}(M_{56}/\mathrm{M}_\odot) = 56.47(M_{\rm WD}/\mathrm{M}_\odot)^3 - 186.30(M_{\rm WD}/\mathrm{M}_\odot)^2 + 206.56(M_{\rm WD}/\mathrm{M}_\odot) - 77.13, \quad (2)$$

to estimate the ^{56}Ni as a function of the detonating WD mass. The large number of digits in each of these coefficients is not meant to represent the significant figures of the ^{56}Ni yield estimation, but merely a consequence of making an accurate fit when using a third-order polynomial. This fit is plotted in Fig. 2 in comparison to the Sim et al. (2010) ^{56}Ni yields (green, filled squares).

Collisions. Another promising way to ignite detonations in double degenerate systems is via collisions, for which we consider the calculations of Kushnir et al. (2013). They generally find that the ^{56}Ni yield only depends on the average mass of the constituents in the collision,

$$M_{\rm avg} = 0.5(M_{\rm WD,1} + M_{\rm WD,2}), \quad (3)$$

where $M_{\rm WD,\,1}$ and $M_{\rm WD,\,2}$ are the primary and secondary masses of the WDs that are colliding, respectively. Again, we fit their ^{56}Ni yield with a third-order polynomial,

$$\log_{10}(M_{56}/\mathrm{M}_\odot) = 16.92(M_{\rm avg}/\mathrm{M}_\odot)^3 - 41.73(M_{\rm avg}/\mathrm{M}_\odot)^2 + 35.16(M_{\rm avg}/\mathrm{M}_\odot) - 10.26. \quad (4)$$

This fit is plotted in Fig. 2 in comparison to the Kushnir et al. (2013) ^{56}Ni yields for equal mass collisions (blue, filled circles) and non-equal mass collisions (red, open diamonds), where we only use their results from high resolution simulations (see their table 1). In the future, a more complete comparison with collision calculations should also include the mass ratio and impact parameter of the collision. For example, in the best-resolved smooth particle hydrodynamic 3D simulations of Raskin et al. (2010), they generally find ∼10 per cent more ^{56}Ni production in equal mass head-on collisions in comparison to Kushnir et al. (2013), and a significant decrease in ^{56}Ni for unequal mass head-on collisions. For the time being, we delay doing a comparison with this other set of calculations until there exists a more complete survey over the full range of parameters.

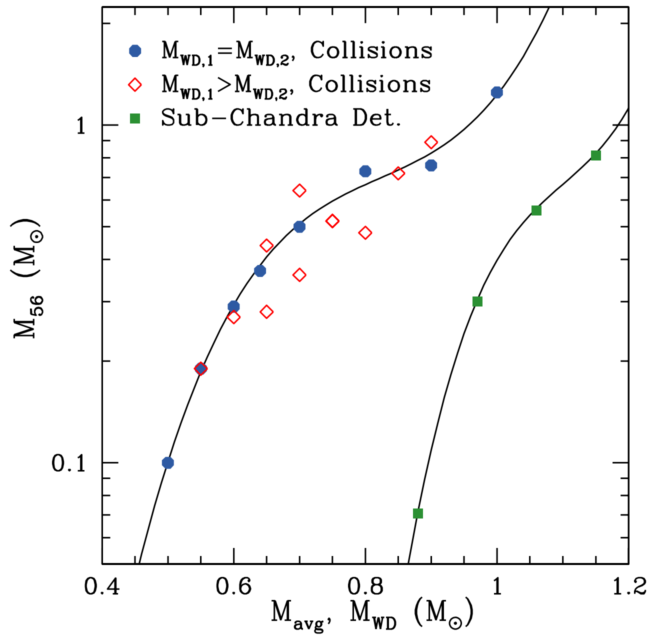

Figure 2. Mass of ^{56}Ni produced for equal mass collisions (blue, filled circles), non-equal mass collisions (red, open diamonds) and sub-Chandrasekhar detonations (green, filled squares). The collision results are taken from the high-resolution simulations of Kushnir et al. (2013) and are plotted against the average mass of the two colliding WDs. The sub-Chandrasekhar detonations are taken from Sim et al. (2010) and are plotted against the mass of the single exploding WD. The solid lines are the fits summarized in equations (2) and (4).

[2] In fact, even among *all* nearby galaxies, the subluminous SN Ia rate has been estimated to be ∼15–30 per cent of all SNe Ia (González-Gaitán et al. 2011; Li et al. 2011a).

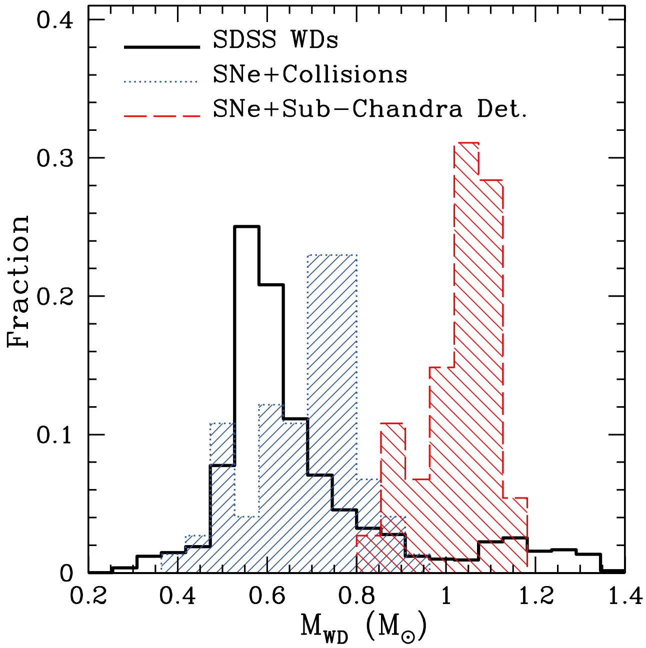

Figure 3. Histograms of the distribution of WD masses $M_{\rm WD}$ from the SDSS WD catalogue (Kepler et al. 2007, black, solid line) as compared to the WD masses needed for sub-Chandrasekhar detonations (Sim et al. 2010, red, dashed line, lightly shaded histogram) and average collision masses $M_{\rm avg}$ needed for head-on collisions (Kushnir et al. 2013, blue dotted line, darkly shaded histogram).

We combine the ^{56}Ni distribution in Fig. 1 with the M_{56} yields from equations (2) and (4) to derive the WD mass distribution needed to reproduce the observations in the sub-Chandrasekhar detonation and collision scenarios, respectively. The results are shown in Fig. 3 (red dashed and blue dotted lines, respectively, both shaded) together with the mass distribution of Galactic field WDs (black, solid line), which we discuss in the following section. Fig. 3 demonstrates that collisions must come from WD–WD binaries with component masses of $M_{\rm avg} \approx 0.75\,{\rm M}_\odot$ in order to reproduce the observed SNe Ia luminosity function, whereas sub-Chandrasekhar detonations must come from WDs that are exploding with masses of $\approx$1.1 M$_\odot$. Thus, if one of these channels is the dominant mechanism for producing SNe Ia, then there must be a reason why this corresponding WD mass is preferentially exploding. In the following sections, we discuss the implications of these mass distributions and investigate what constraints they allow us to place on the relation of these scenarios to the observed SNe Ia.

3.1 Comparisons to field WDs

We next compare these inferred mass distributions with the volume-corrected mass distribution of spectroscopically confirmed WDs from Sloan Digital Sky Survey Data Release 4 (Kepler et al. 2007). Summing all DA and DB WDs, the total sample contains over 1800 WDs. Plotting the corresponding histogram in Fig. 3 (black, solid line), the average mass of field WDs is $\approx$0.55–0.60 M$_\odot$, and it is clearly different than either the sub-Chandrasekhar detonation or collision scenarios. In particular, this comparison shows that collisions between average-mass WDs of $\sim$0.6 M$_\odot$ produce too little ^{56}Ni to power the average observed SNe Ia. Thus, if collisions are responsible for the majority of SNe Ia that we see, they must pick out high-mass progenitors and collisions must be suppressed in binaries with average-mass WD constituents.

Although the mass distribution inferred for sub-Chandrasekhar detonations is also inconsistent with the overall field WD population, as one would expect naively, its peak at $\approx$1.1 M$_\odot$ is not too dissimilar from the secondary high-mass peak in the field WD population at $\approx$1.2 M$_\odot$. It has been suggested that the high-mass peak is due to mergers of lower mass WDs (Vennes 1999; Liebert, Bergeron & Holberg 2005), which may indicate a connection between mergers and sub-Chandrasekhar detonations. The implication may be that either (1) SN Ia progenitors are coming from the same binary mergers that would produce these massive WDs or that (2) the WDs merged first and then the explosion was triggered later, as in a double detonation. In the first case, it is unclear why some WDs would explode upon merger (producing SNe Ia) while other WDs would produce the massive field WDs. In the second case, it seems like a specialised set of circumstances would be needed to first produce massive WD via a merger and then have an event that subsequently triggered an explosion.[3] On the other hand, it has also been argued that the kinematics of massive WDs are consistent with single-star evolution (Wegg & Phinney 2012) rather than being the product of mergers. The suggestion is then that perhaps SNe Ia come from more massive WDs that are simply the result of more massive main sequence stars. Whatever the conclusion is, the rough similarity of these peaks clearly requires more investigation, some of which we conduct in the next section.

4 ^{56}NI YIELDS FROM BINARY POPULATIONS

So far, we have made comparisons to field WDs, but SN Ia progenitors are expected to be in binary (or perhaps triple) systems. We assess the impact of binarity with a Monte Carlo binary mass distribution calculation. Instead of performing a detailed population synthesis (e.g. Belczynski et al. 2008, and references therein), we use a simpler model to focus on certain generic aspects of WD–WD binary populations in the absence of mass transfer and binary interactions. This allows us to estimate the average and total mass in WD–WD binaries for comparisons with explosion scenarios, and to explore the impact of age and star formation history on the expected ^{56}Ni yields.

Our analysis proceeds as follows. First, we consider a distribution of main-sequence stars with mass M_1, which obeys a Salpeter initial mass function,

$$dN/dM_1 \propto M_1^{-2.35}. \qquad (5)$$

Next, we consider companion masses M_2, which are assigned a flat distribution in mass (Duchêne & Kraus 2013), so that the probability $P(q)$ is constant, where $q = M_2/M_1 \leq 1$. For a given binary, we can evaluate the final masses of each of the WDs that are created using the initial mass–final mass relation (Kalirai et al. 2008),

$$M_{{\rm WD},i}/{\rm M}_\odot = 0.109 M_i + 0.394. \qquad (6)$$

Using the relation from Catalán et al. (2008) would lead to nearly identical results. We assume a maximum mass of 7 M$_\odot$ for M_1 and M_2 to produce a C/O WD. The lower mass limit is taken to be 0.9 M$_\odot$ so as to focus on progenitors of C/O WDs rather than

[3] Later, we discuss scenarios that have been explored in population synthesis calculations, which may indeed allow the WD to accrete and become more massive before unstably igniting, as is needed for this scenario.

helium WDs. The time-scale for formation of a double degenerate binary is

$$t_{\rm form} = t_{\rm birth} + 10 \left(\frac{M_2}{{\rm M}_\odot}\right)^{-2.5} {\rm Gyr}, \quad (7)$$

where $t_{\rm birth}$ is the time when the main-sequence binary was first created. Note that $t_{\rm form}$ is controlled by mass M_2, since the lower mass secondary takes longer to evolve off the main sequence. Finally, there is an explosion time given by the sum of the formation time and the time-scale for ignition of a detonation or a collision,

$$t_{\rm exp} = t_{\rm form} + t_{\rm ign}. \quad (8)$$

Given this set of prescriptions, we can assemble a large number of WD binaries with a distribution of masses and associated time-scales using Monte Carlo methods. We can then estimate the current distribution now at time $t_{\rm now} \approx 13.7$ Gyr by asking which binaries have $t_{\rm now} > t_{\rm form}$ and $t_{\rm now} < t_{\rm exp}$, in other words, those binaries that have had enough time to produce double degenerates, but have not yet exploded as SNe Ia. In this way, we estimate a WD–WD binary mass distribution for comparison with the sub-Chandrasekhar detonation and collision scenarios.

This analysis omits many features that are present in more sophisticated population synthesis calculations (e.g. Belczynski et al. 2008, and references therein). One of the likely most important omissions is mass transfer. In many population synthesis calculations, one of the aims is to reproduce observed distributions, but that is not our main point of study here. We instead want to focus on how well the observed distributions can be understood just from stellar age effects. In cases where there is disagreement between our models and the observed distributions, it provides intuition about where mass transfer could be especially important. If in contrast we include mass transfer from the outset, it would introduce more uncertainties in these comparisons because there are many things still not understood about mass transfer (e.g. how to treat the evolution when the accretion rate is super-Eddington, or how much mass is conserved in nova events). For readers interested in how this picture changes once mass transfer is included, we recommend comparing our results to Ruiter et al. (2013).

4.1 ^{56}Ni from collisions

In Fig. 4, we compare the ^{56}Ni yield expected from our Monte Carlo calculations for collisions to the ^{56}Ni distribution we derived from the volume-limited sample of SNe Ia as was shown in Fig. 1 (black, solid line). For these calculations, we set $t_{\rm ign} = 100$ Myr, although we find that the results do not depend sensitively on this assumption as long as $t_{\rm ign} \lesssim t_{\rm form}$. We focus on cases were $t_{\rm ign}$ is relatively short since this is expected for the collision scenario (Katz, Dong & Malhotra 2011), and for sub-Chandrasekhar detonations (which will be addressed in the next section), it will allow us to assess whether the formation time-scale alone is sufficient to match the observed ^{56}Ni distribution. To set $t_{\rm birth}$, we assume a burst of star formation at some time in the past at $t_{\rm burst}$ which then lasts for 1 Gyr with a flat probability over this time. By varying $t_{\rm burst}$, we can investigate the impact of age on the resulting distribution of WD–WD binary masses. Fig. 4 plots histograms for $t_{\rm burst} = 13.7$ Gyr (blue, dotted line), 3 Gyr (green, solid line) and 1 Gyr (red, dashed line). Each of these histograms has been arbitrarily normalized to ease comparison with the observed distribution. Although this is a simple model, intuition about more complicated star formation histories can be gained by simply considering the integral of many of these individual star bursts.

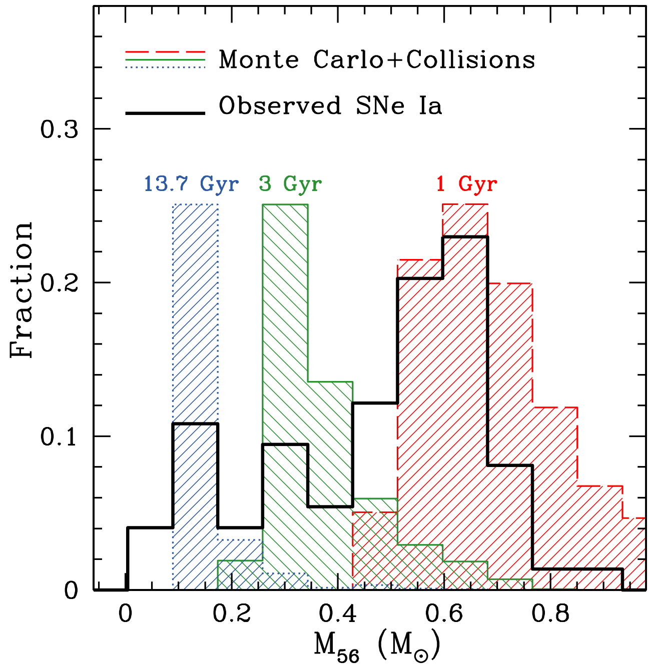

Figure 4. Histograms of the distribution of ^{56}Ni from Monte Carlo binary estimates using the collision scenario (Kushnir et al. 2013). The black solid line is the observed ^{56}Ni distribution (from Fig. 1) and the coloured histograms correspond to calculations using a burst of star formation at times of $t_{\rm burst} = 13.7$ Gyr (blue, dotted line), 3 Gyr (green, solid line) and 1 Gyr (red, dashed line). The colour histograms have been arbitrarily normalized to ease comparison.

Fig. 4 shows that to produce typical SNe Ia, collisions must occur between stars that formed rather recently, of the order of ∼1 Gyr ago. Although this is obviously similar to our previous conclusion that high-mass WDs are needed for the collision scenario to produce most SNe Ia, this comparison makes it explicit just how limiting this statement is. In investigations of SN Ia rates, there is evidence that SNe Ia must be occurring on both relatively short and long time-scales in comparison to the time of star formation (Mannucci et al. 2005; Scannapieco & Bildsten 2005; Mannucci, Della Valle & Panagia 2006; Sullivan et al. 2006; Maoz & Mannucci 2012). In this context, we find that collisions can only produce normal SNe Ia as a rather prompt contribution. Conversely, this makes it difficult to see how collisions can produce a significant number of normal SNe Ia in a delayed component unless there is some mechanism that makes collisions between higher mass WDs more likely.

On the other hand, Fig. 4 also demonstrates that for sufficiently old stellar environments (blue, dotted histogram), collisions may be important for producing low-luminosity SNe Ia, and indeed they have a ^{56}Ni yield consistent with that seen from 1991bg-like events. The fact 1991bg-like SNe happen almost exclusively in early-type galaxies makes collisions an enticing explanation. It has been speculated upon before that 1991bg-like events are from WD–WD collisions, but in the context of more massive collisions that are inefficient at producing ^{56}Ni (Pakmor et al. 2010). The problem with this hypothesis is that $t_{\rm ign}$ must be much longer than $t_{\rm form}$ to have such massive (∼0.9 M$_\odot$) WDs merging in old stellar environments. Pakmor et al. (2010) note this problem and speculate that the collision time-scale may just naturally be long. Unfortunately, this does not explain why evidence of many more slightly lower mass collisions are not seen, since they would be favoured by the initial mass function. If the ^{56}Ni yields of Kushnir et al. (2013) are correct, then this problem is alleviated because *1991bg-like events naturally match what it is expected for collisions between the most abundant mass WDs*. An important area of future research will be to investigate the expected rate of such collisions to understand whether they can be as high as the rates seen by LOSS in early-type galaxies.

Although we were forced to assume a nickel yield for six of these 1991bg-like events, changing the specific amount of the yield does not dramatically impact our conclusion here. Looking at nickel yields from collisions in Fig. 2, $M_{56} \gtrsim 0.3\,\mathrm{M_\odot}$ would be required for the average WD mass to be increased appreciably so that they could require a slightly younger stellar population. Although the 1991bg-like events may produce $M_{56} \approx 0.2\,\mathrm{M_\odot}$, it is extremely unlikely they can produce these much higher amounts.

4.2 ^{56}Ni from sub-Chandrasekhar detonations

For the sub-Chandrasekhar detonation scenario, there are two potential masses we could identify for the triggering of the detonation, either (1) the primary mass or (2) the total mass of the binary,

$$M_{\rm tot} = M_{\rm WD,1} + M_{\rm WD,2}. \qquad (9)$$

In the first case, we know from Fig. 3 that the average mass of the detonating primary must be $\approx$1.1 $\mathrm{M_\odot}$. Although it is possible that $t_{\rm ign}$ for such a primary could be sufficiently long to allow such high-mass WDs to last long enough to produce typical SNe Ia in both young and old stellar environments, it is not immediately clear why an $\approx$1.1 $\mathrm{M_\odot}$ primary would be favoured for explosion in comparison to, say, an $\approx$1.0 $\mathrm{M_\odot}$ primary without appealing to some sort of binary interactions. In the next section, we discuss the results of population synthesis analysis which takes this into account, but for the simpler population model we are using, this physics is outside the context of what we are investigating.

So instead, we focus on the latter case of using $M_{\rm tot}$ to estimate the ^{56}Ni production. The idea here would be that a WD–WD merger could potentially be qualitatively similar to the mass budget of just combining the two WDs. One should be careful here because exploding two 0.6 $\mathrm{M_\odot}$ WDs separately will yield much less ^{56}Ni mass than exploding one 1.2 $\mathrm{M_\odot}$ WD. Using $M_{\rm tot}$ corresponds to the assumption that following the merger the density reaches a configuration roughly like the larger mass object, which may require some time to adjust to the increase in mass (e.g. Shen et al. 2012). With these caveats in mind, we show the results of our Monte Carlo calculations in Fig. 5. In this case, the average ^{56}Ni yield seen in observations is consistent with WDs from stars that formed $t_{\rm burst} \approx$ 5–7 Gyr ago (red, dashed line), since this is what is needed for binaries with $M_{\rm tot} \approx 1.1\,\mathrm{M_\odot}$. We conclude from this comparison that it is at least plausible that *the average SNe Ia could be explained by sub-Chandrasekhar mergers as long as the total mass of the binary corresponds to the explosion mass*. On the other hand, going to especially old stellar populations (blue, dotted line) will still make an SNe Ia with a relatively normal amount of ^{56}Ni production ($M_{56} \sim 0.4\,\mathrm{M_\odot}$), so it is difficult to explain the especially subluminous SNe Ia if the entire mass of the binary is involved in the detonation and we limit ourselves to C/O WDs.

5 CONCLUSION AND DISCUSSION

We have conducted an initial investigation exploring the implications of the collision and sub-Chandrasekhar detonation scenarios as possible progenitors of SNe Ia. First, we derived the ^{56}Ni distribution from a volume-limited sample of SNe Ia (Fig. 1). This was used to infer the distribution of WD masses that must be exploding in each scenario in order to match the observations, and then to make comparisons with the observed field WD mass distribution (Fig. 3). Using a simple Monte Carlo population analysis, we investigated the ^{56}Ni yield as a function of stellar age to explore the viability of each scenario.

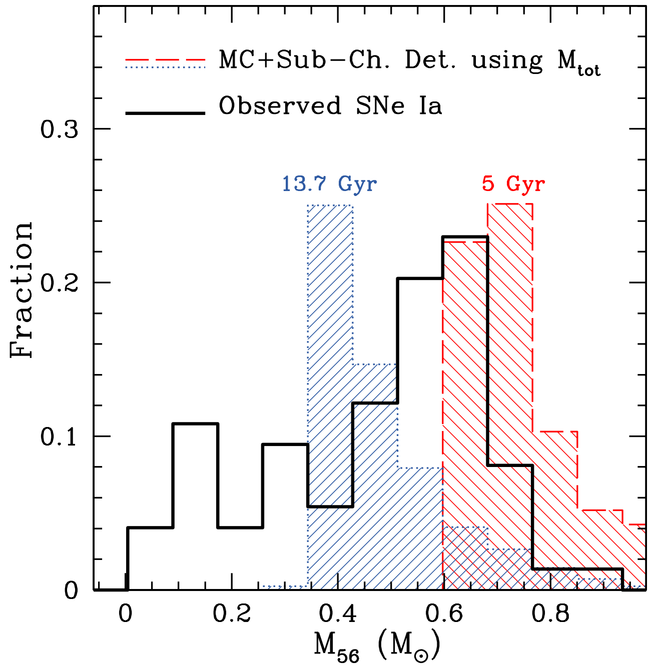

Figure 5. Similar to Fig. 4, but instead for the sub-Chandrasekhar detonation scenario (Sim et al. 2010). The coloured histograms correspond to calculations using a burst of star formation at times of $t_{\rm burst}$ = 13.7 Gyr (blue, dotted line) and 5 Gyr (red, dashed line).

5.1 Sub-Chandrasekhar detonation scenario

Our main conclusion for the sub-Chandrasekhar detonation scenario (Sim et al. 2010) is that it requires the explosion of WDs with an average mass of $\approx$1.1 $\mathrm{M_\odot}$. This is clearly inconsistent with the general mass distribution of *single*-field WDs, but may be similar to a population of more massive WDs which have a distribution peak at around $\approx$1.2 $\mathrm{M_\odot}$ (Fig. 3). We then explored the ^{56}Ni yield from populations of various ages and found that a burst of star formation at $t_{\rm burst} \approx$ 5–7 Gyr ago would allow sub-Chrandrasekhar detonations to explain typical SNe Ia (Fig. 5). Although this connection is enticing, there are problems that still need to be sorted out to understand its importance. If two WDs merge, the density of the resulting WD that experiences the detonation need not be equivalent to a WD that has a mass which is the sum of the two constituents. Our analysis would therefore benefit from some conversion factor, which would give a better estimate of how much material is at a sufficiently high density to produce ^{56}Ni. For example, detailed studies of WD mergers and the conditions needed for ignition (e.g. Dan et al. 2013; Zhu et al. 2013, and references therein) should be folded into such future work. If the conversion factor is low (for example, if ignition occurs when a large fraction of the material in a merging WD–WD binary is still at relatively low densities), then it may be related to some of the lower luminosity SNe Ia that are difficult to explain with sub-Chandrasekhar detonations using our simplistic model.

Another scenario for getting a sub-Chandrasekhar detonation, which was outside the context of our simple population model (as discussed in Section 4.2, this would require binary interaction physics or a long $t_{\rm ign}$), was that the primary mass could be the determining factor for estimating the ^{56}Ni yield. Ruiter et al. (2013) considered this case, and also concluded that the average exploding WD mass much be $\approx 1.1\,{\rm M}_{\odot}$. Using population synthesis models, it was found that the most promising avenue for creating such a progenitor was by taking a somewhat smaller mass WD ($\approx 0.8-0.9\,{\rm M}_{\odot}$), increasing its mass up to $\approx 1.1\,{\rm M}_{\odot}$ via helium-rich accretion from its companion, and then eventually merging with that companion (Ruiter et al. 2013). Whether or not this scenario happens robustly in detailed accretion models (for example, that there is little mass-loss during helium accretion as assumed in these population synthesis calculations) requires more investigation.

Instead of a merger, yet another way to ignite the primary in a sub-Chandrasekhar detonation would be with a double detonation, where a helium-rich layer is accreted and detonated, triggering the C/O core (Woosley & Weaver 1994; Livne & Arnett 1995). Although in the past this mechanism has been disfavoured because it produces colours and spectra that do not match normal SNe Ia (Kromer et al. 2010), more detailed treatments of the helium burning suggest that this problem may be alleviated (Townsley, Moore & Bildsten 2012; Moore, Townsley & Bildsten 2013). Whatever the answer may be, the fact remains that $\approx 1.1\,{\rm M}_{\odot}$ WDs must somehow be favoured for exploding in sub-Chandrasekhar detonations in comparison to any other mass. The results of our work emphasize the importance of this litmus test for any future similar classes of models.

5.2 Collision scenario

For the collision scenario (Kushnir et al. 2013), we find that the average mass of an exploding WD must be $\approx 0.75\,{\rm M}_{\odot}$. Although collisions could therefore produce typical SNe Ia in especially young environments, it is hard to see how collisions could generate a significant fraction of the normal SNe Ia that we observe. We note that DB WDs and magnetic WDs are generally more massive than DA and non-magnetic WDs (Wickramasinghe & Ferrario 2000; Kepler et al. 2007), but there is not a clear reason why these populations should be expected to participate in collisions more often than regular WDs. There are several ways to alleviate this inconsistency: the ^{56}Ni yields in hydrodynamic calculations are too low by $\approx 0.3\,{\rm M}_{\odot}$ (which seems unlikely given the convergence considerations in Raskin et al. 2010; Kushnir et al. 2013), the conversion from $\Delta m_{15}(B)$ to M_{56} (equation 1) is too high by the same factor, or the physics associated with glancing collisions that yield subsequent mergers produce much more ^{56}Ni, making them more akin to the sub-Chandrasekhar detonations also discussed in our work. As these uncertainties are more fully investigated, it may be worth revisiting our conclusions about the collision scenario.

Our conclusions do not rule out the collision mechanism for producing some fraction of SNe Ia. In fact, low-luminosity 1991bg-like SNe Ia with $M_{56} \lesssim 0.2\,{\rm M}_{\odot}$ may be naturally explained by collisions in an old stellar environment, as shown in Fig. 4 and discussed more extensively in Section 4.1. This important connection should be explored by future investigations of this subclass of SNe Ia.

5.3 Missing details and future work

The investigation presented here uses a simple analysis to compare WD populations and explosion scenarios. Additional details should be included in future, more comprehensive calculations. For example, future similar work could use a more realistic star formation history (for example, see Ruiter, Belczynski & Fryer 2009) to explore the details of the resulting ^{56}Ni distribution. In the Monte Carlo analysis, we used a bursty star formation rate set at various times in the past. This allowed us to demonstrate that a star formation rate more strongly peaked at earlier times would favour lower mass progenitors at later times since they take longer to evolve. *This naturally predicts lower luminosity SNe Ia in older populations because higher mass systems evolve more rapidly.* This may explain why late-type hosts have systematically brighter SNe Ia than early-type hosts, why the brightest events also occur in these kinds of galaxies (e.g. Howell et al. 2007), and why 1991bg-like SNe Ia happen almost exclusively in early-types galaxies. Detailed differences between early- and late-type may be an important tool for distinguishing between SNe Ia progenitor scenarios.

Another factor we have not completely accounted for is the time-scale for detonation or collision in each scenario, and as a function of the WD masses. As long as $t_{\rm ign}$ is less than $t_{\rm form}$ (as we assumed in our work) this is a relatively small correction, but this need not be the case for all mass ratios. In particular, higher mass primaries have a wider range of possible companion masses. The 'eccentric Kozai mechanism' (EKM), which promotes very strong eccentricity maxima and collisions in the inner binary of triple systems (Ford, Kozinsky & Rasio 2000, Katz et al. 2011, Lithwick & Naoz 2011; Naoz et al. 2011, 2013), favours high mass ratio binaries and is suppressed over a wide range of tertiary inclinations when the masses of the inner binary are approximately equal (see Naoz et al. 2013; Shappee & Thompson 2013). If EKM eccentricity maxima generically lead to collisions, then this would favour collisions in systems with higher $M_{\rm avg}$, which might help alleviate some of the inconsistencies seen in Fig. 4. The EKM has also recently been shown to be enhanced over a broad range of parameter space in quadruple systems (Pejcha et al. 2013), potentially favouring WD–WD collisions in systems with initial mass distributions that might be different from normal binaries.

The machinery we have developed can be applied to new theoretical calculations of collisions and detonations, as well as to test other novel double degenerate scenarios. Some of the questions that would be particularly important to work out for inclusion in future calculations include the following.

(i) In collision scenarios, what is the ^{56}Ni production as a function of the impact parameter and mass ratio?

(ii) In collision scenarios, how does the time-scale for the collision ($t_{\rm ign}$ in our model) depend on the mass ratio?

(iii) If 1991bg-like SNe Ia are explained as collisions in old stellar environments, do their rates in late-type galaxies (which still have an old stellar component) match this hypothesis?

(iv) In sub-Chandrasekhar detonation scenarios, what is the expected ^{56}Ni as a function of the $M_{\rm tot}$, and how does it depend on the mass ratio and time of ignition?

(v) Extrapolating Fig. 2 to high masses results in a large ^{56}Ni yield for either scenario. As super-Chrandrasekhar SNe Ia are better characterized in comparison to regular SNe Ia, can these be naturally explained by either detonation or collision scenarios?

As these questions are better investigated, it should be worth revisiting and reevaluating many of the conclusions we have made here to gain a better understanding of what role double degenerates play in producing SNe Ia.

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