SOME CONSTRAINTS ON THE LOWER MASS LIMIT FOR DOUBLE-DEGENERATE PROGENITORS OF TYPE Ia SUPERNOVAE

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ABSTRACT

Recent theoretical and observational studies both argue that the merging of double carbon-oxygen white dwarfs (WDs) is responsible for at least some Type Ia supernovae (SNe Ia). Previous (standard) studies of the anticipated SN birthrate from this channel have assumed that the merger process is conservative and that the primary criterion for explosion is that the merged mass exceeds the Chandrasekhar mass. Han & Webbink demonstrated that mass transfer and merger in close double WDs will in many cases be non-conservative. Pakmor et al. further suggested that the merger process should be violent in order to initiate an explosion. We have therefore investigated how the SN Ia birthrate from the double-degenerate (DD) channel is affected by these constraints. Using the binary-star population-synthesis method, we have calculated the DD SN Ia birthrate under conservative and non-conservative approximations, and including lower mass and mass-ratio limits indicated by recent smoothed-particle-hydrodynamic calculations. The predicted DD SN Ia rate is significantly reduced by all of these constraints. With dynamical mass loss alone (violent merger) the birthrate is reduced to 56% of the conservative rate. Requiring the mass ratio \( q > 2/3 \) further reduces the birthrate to 18% that of the standard assumption. An upper limit of 0.0061 SNeIaM, or a Galactic rate of \( 4.6 \times 10^{-4} \text{yr}^{-1} \), might be realistic.

Key words: binaries: close – stars: evolution – supernovae: general

Online-only material: color figures

1. INTRODUCTION

The double-degenerate (DD) merger was suggested as a possible channel for Type Ia supernovae (SNe Ia) in the early 1980s (Tutukov & Yungelson 1981; Iben & Tutukov 1984; Webbink 1984). In this DD model, two carbon-oxygen (CO) white dwarfs (WDs) can produce an SN Ia while merging if their total mass is larger than the Chandrasekhar mass \( M_{\text{ch}} \). The DD model can naturally explain the lack of H and He emission in the spectra of SNe Ia and some super-luminous SNe Ia, but it has major difficulty in explaining the similarities of SNe Ia with other types of observations (Yungelson et al.1994; Han 1998; Nelemans et al. 2001; Ruiter et al. 2009; Wang et al. 2010; Yu & Jeffery 2010), theoretical studies suggest that the merger of two WDs is more likely to lead to an accretion-induced collapse (AIC) to form a neutron star (Nomoto & Iben 1985; Saio & Nomoto 1985; Timmes et al. 1994). Consequently, the DD model has been disadvantaged in comparison to the single-degenerate (SD) model for a long time (Wang & Han 2012).

Piersanti et al. (2003) suggested that, under the right conditions, the DD merger process could be quite violent and lead to an SN Ia explosion rather than AIC (see also Yoon et al. 2007; Shen et al. 2012). Fully three-dimensional simulations of a violent merger of two CO WDs by Pakmor et al. (2010, 2011) show that the merger of two equal-mass CO WDs \( \sim 0.9 M_{\odot} \) can explain the formation of subluminous 1991bg-like events (see also van Kerkwijk et al. 2010). The Pakmor et al. (2012) simulation of a DD merger with masses of 1.1 \( M_{\odot} \) and 0.9 \( M_{\odot} \) shows good agreement with properties of normal SNe Ia. Observationally, some known or potential DD systems such as WD 2020-425 (Napiwotzki et al. 2007), V458 Vulpeculae (Rodríguez-Gil et al. 2010), SBS1150+599A (Tovmassian et al. 2010), and GD687 (Geier et al. 2010) represent good candidates for SN Ia progenitors since they have total masses close to \( M_{\text{ch}} \) and orbital periods short enough to merge within a Hubble time. Furthermore, extensive searches have found no surviving companion to the Type Ia supernovae responsible for SNR 0509-67.5 (Schaef er & Pagnotta 2012) or SN 1572 (Kerzendorf et al. 2012), whence it is argued that the progenitors must have been DD systems. Hence, it appears that at least some, if not most, SNe Ia come from DD mergers.

Previous studies for the DD model generally assume that an SN Ia is produced if the total mass of a DD system is larger than \( M_{\text{ch}} \). This assumption implies that the DD merger process is always conservative. However, if accretion is spherically symmetric, mass transfer can be dramatically non-conservative both during stable mass transfer and in a violent merger. Han & Webbink (1999, hereafter HW) studied the stability and energetics of mass transfer in double WDs. They showed that the expelled mass fraction of an interacting double WD depends on the component masses and can be as large as 50% of the donor for a system with masses of 1 \( M_{\odot} \) and 0.5 \( M_{\odot} \). Meanwhile, smoothed-particle-hydrodynamic (SPH) simulations (Yoon et al. 2007; Pakmor et al. 2011) have shown that not all double CO WDs with a total mass larger than \( M_{\text{ch}} \) can produce SNe Ia. For example, Pakmor et al. (2011) find that only...
double CO WDs in which the more massive white dwarf exceeds \( \sim 0.9 M_\odot \) and the mass ratio roughly exceeds 0.8 robustly reach the conditions required for initiating a detonation, leading to an SN Ia explosion. Obviously, some additional constraints should be placed on the DD model for triggering SNe Ia.\(^6\)

In Section 2 we investigate the merger mass of double WDs including non-conservative mass transfer, and we examine the impact of these constraints and those arising from SPH simulations on the SNe Ia birthrate in Section 3. Conclusions are drawn in Section 4.

2. THE MERGER MASS

As the orbit of a double WD system decays due to the emission of gravitational radiation/waves, the less massive component will be the first to fill its Roche lobe and become the mass donor; the more massive component becomes the accretor. Unlike non-degenerate donor stars in other compact binaries, the WD donors in double WDs lie deeper within the potential well of the accreting star, resulting in important consequences for mass transfer. Assuming energy conservation and hence no energy sources other than gravitational potential energy are at play, HW analyzed the initial stability of this mass transfer and the fraction of the mass-transfer stream to be expelled from the binary. From this point of view, the mass transfer is conservative if the accretion luminosity is less than the Eddington limit. Any accretion luminosity in excess of the Eddington limit is assumed to be absorbed in the accretion flow. In terms of energetics, radiative losses represent accretion energy not used to power a mass outflow (HW, Equation (21)). The fraction of matter accreted by the primary is used to power the outflow and can be determined from Equation (22) of HW. For component masses \( M_1 \) (accretor) and \( M_2 \) (donor), we adopt Equations (17), (22), and (23) of HW to calculate the mass transfer rate, \( \dot{M}_2 \), and the fraction of matter to be accreted by the primary,\(^7\) \( \beta \).

There are two regimes for computing the final total mass of the merger, \( M \). If the merger process is dynamical, \( \beta \) can be applied as a single step process and \( M = M_1 + \beta M_2 \). If mass transfer is stable, \( M \) is obtained by integrating over the mass-transfer epoch,\(^8\) using \( M = M_1 + \int \beta(t) M_2(t) \, dt \).

3. TYPE Ia SUPERNOVAE FROM THE DD MODEL

3.1. The Formation of Double CO WD Systems

To investigate the SN Ia birthrate due to DD mergers, we require a population of close double CO WD binaries to be formed from interactions in a population of primordial binary stars (e.g., Han 1998). We first perform a Monte Carlo simulation to obtain a stellar population, then evolve them in a rapid binary evolution code (RBEC; Hurley et al. 2000, 2002) to obtain a sample of close CO WD systems.

In the Monte Carlo simulation, all stars are assumed to be members of binaries and have circular orbits. The primaries follow the initial mass function of Miller & Scalo (1979) and are generated according to the formula of Eggleton et al. (1989), in the mass range 0.08–100 \( M_\odot \). The secondary mass, also with a lower limit of 0.08 \( M_\odot \), is then obtained from a constant mass-ratio distribution. The distribution of orbital separations \( a \) is taken to be constant in \( \log a \) for wide binaries. This separation distribution has been used in many Monte Carlo simulations and implies an equal number of wide binary systems per logarithmic interval and approximately 50% of stellar systems with orbital periods less than 100 yr (Han 1998). Long-orbital-period binaries are effectively single stars.

The formation of close double CO WD systems depends significantly on the critical mass ratio for dynamical instability \( q_c \) and common envelope (CE) evolution (Han 1998). A binary experiences stable Roche lobe overflow (RLOF) when \( q < q_c \) and CE evolution otherwise, where \( q = \text{donor}/\text{accretor} \). In this study we adopt Equation (57) of Hurley et al. (2002) for \( q_c \) when the mass donor is on the first or asymptotic giant branch (AGB), and let \( q_c = 4 \) when the mass donor is on the main sequence or in the Hertzsprung gap, as supported by detailed binary evolution studies (Han et al. 2000; Chen & Han 2002, 2003). For CE evolution, we use the standard energy formalism (van den Heuvel 1976; Webbink 1984; Livio & Soker 1988), that is, the CE is ejected if \( \Delta E_{\text{orb}} \geq E_{\text{bind}} \), where \( \Delta E_{\text{orb}} \) is the orbital energy released, \( \Delta E_{\text{orb}} \) is the CE ejection efficiency, and \( E_{\text{bind}} \) is the binding energy of the envelope and can be written as \( G M_a M_{\text{en}}/(\lambda R_d) \) (where \( M_a, M_{\text{en}}, \) and \( R_d \) are the mass, envelope mass, and radius of the donor, respectively, and \( \lambda \) is a structure parameter that depends on the evolutionary stage of the mass donor). We combine \( \alpha_{\text{ce}} \) and \( \lambda \) into one free parameter, setting \( \alpha_{\text{ce}} \lambda = 1.5 \) to reproduce the number of the DD objects in the Galaxy as in previous studies (Wang et al. 2009a).

RBEC distinguishes three types of WDs, namely helium (expected only in binaries), CO, and oxygen-neon (ONe), respectively. The critical condition for CO and ONe WDs is the core mass at the base of AGB, \( M_{\text{C,AGB}} \). CO WDs are produced when \( M_{\text{C,AGB}} < 1.6 M_\odot \), and ONe WDs when \( 1.6 M_\odot \leq M_{\text{C,AGB}} < 2.5 M_\odot \), where \( M_{\text{C,AGB}} \) is given in Equation (66) of Pols et al. (1998). The mass of the CO core, and the final mass of CO WDs is determined by the \( L-M \) relation; see Equations (37) and (39) of that paper.

3.2. Constraints on the Progenitors of SNe Ia

There are two basic constraints on double CO WDs as the progenitors of SNe Ia in the conservative case: (1) \( M_1 + M_2 > M_{\text{ch}} \) and (2) the CO WDs are close enough to merge in a Hubble time. The timescale for two components to merge by gravitational wave radiation, \( t_{\text{GW}} \), is written as (Landau & Lifshitz 1971)

\[
    t_{\text{GW}} = 8 \times 10^7 \times \left( \frac{M_1 + M_2}{M_1 M_2} \right)^{1/3} \frac{1}{P^{1/3}},
\]

where \( P \) is the orbital period in hours, \( t_{\text{GW}} \) in years, and \( M_1, M_2 \) in solar mass.

In the non-conservative assumption, constraint (1) should be redefined as the final mass \( M > M_{\text{ch}} \) (see Section 2). Furthermore, AIC should be avoided in order to successfully trigger an SN Ia. We therefore need additional constraints from dynamical simulations. Pakmor et al. (2010, 2011, 2012) showed that an initial detonation at the onset of C ignition

\(^6\) From the point of view of preventing an off-center C ignition, Yoon et al. (2007) favored less massive double CO WDs to produce SNe Ia. Since an off-center C ignition is almost inevitable (Shen et al. 2012), and much of the physics for the thermal evolution of merger remnants is unclear, we only consider here the constraints from Pakmor et al. (2011).

\(^7\) Note that the model of HW takes the accretion to be spherical. If mass transfer is through a disk, then excess energy can be radiated away from the poles and \( \beta \) may not be appropriate.

\(^8\) The fitting formulae and a table for the merger mass from the two regimes for various component masses may be obtained from xuefeichen717@hotmail.com.

\(^9\) We adopt \( M_{\text{B}} = 1.378 M_\odot \) following Han & Podsiajlo (2004), Meng et al. (2009), and Wang et al. (2009b).
can lead the DD merger to avoid AIC and explode, and that DDs with $M_1 \geq 0.9 M_{\odot}$ and a mass ratio $M_1/M_2 \geq 0.8$ can achieve conditions for initiating such a detonation. Their studies also showed that mergers with $M_1 \simeq 0.9 M_{\odot}$ are very promising candidates for explaining subluminous SNe Ia, while a normal SN Ia can be produced from the double CO WDs with $M_1 = 1.1 M_{\odot}$. Since the SN Ia luminosity is determined by the amount of $^{56}$Ni synthesized in the explosion, the simulation results seem to indicate that the primary mass is related to the final production of $^{56}$Ni, and therefore determines whether a normal or subluminous SN Ia is produced. Meanwhile, we do see a lot of variation in SN Ia light curves, and thus one might expect to see a variety among exploding WD masses provided by the DD models. In the absence of other constraints, we study the SN Ia birthrate assuming two lower mass limits for the DD accretor, i.e., $M_1 > 0.9$ or $1.0 M_{\odot}$, respectively.

Another constraint from the SPH simulations is the mass ratio of the CO DDs, $q = M_2/M_1$. It has a critical value, $\approx 0.8$, below which the merger is not violent enough to ignite a detonation (Pakmor et al. 2011).\footnote{Pakmor et al. (2011) found that the critical value of $q$ probably changes with primary WD mass, i.e., more massive primaries can merge with lower mass ratios.} The relation between the violence of a merger and the mass ratio can be simply understood from Figure 2 of HW. In the dynamical instability region, $\zeta_{ad} - \zeta_L < 0$, where $\zeta_{ad}$ and $\zeta_L$ are the adiabatic mass-radius exponent of the donor and the mass-radius exponent of its Roche radius, respectively. With the mass ratio closer to unity, the value of $|\zeta_{ad} - \zeta_L|$ becomes increasingly larger. Since it is a negative number, the process of self-amplifying $M_2$ (Equation (1) in that paper) is thus faster and faster, resulting in a more and more violent merger process. We arbitrarily relax the critical mass ratio from 0.8 to 2/3 in our study to give an upper limit for the SN Ia birthrate from the SPH simulations.

In brief, based on the sample of double CO WDs which can merge in a Hubble time, we compute the SN Ia birthrate for the following cases:

1. $M = M_1 + \beta M_2 \geq M_{\Delta}$;
2. $M = M_1 + \int \beta(t) M_2(t) dt \geq M_{\Delta}$;
3. as case (2) with $M_1 \geq 0.9 M_{\odot}$. We choose case (2) as the basic constraint since it includes a larger parameter space than case (1) (see Figure 1). The overall SN Ia rate from case (2) can then be considered as an upper limit from the non-conservative assumption;
4. similar to case (3) but $M_1 \geq 1.0 M_{\odot}$; and
5. an additional constraint, $q = M_2/M_1 \geq 2/3$, is placed on case (3).

Figure 1 shows these constraints in the $M_1-M_2$ plane (left panel), as well as CO DDs with a total mass $M_1 + M_2 > M_{\Delta}$ which can merge in a Hubble time (right panel). To obtain these DDs, we generate a population of $10^5$ binaries (with a total mass of $\approx 1.26 \times 10^3 M_{\odot}$) as described in Section 3.1 and evolve them in RBEC. These DDs cover a wide range in the $M_1-M_2$ plane, then have a large range of $\beta$ values. For $q = 2/3$, $\beta$ decreases from 0.7 to 0.54 as $M_1$ increases from 0.827 to 1.2 $M_{\odot}$. The overall parameter spaces of SN Ia progenitors in cases (1)-(4), i.e., to the right of the red lines, are reduced by different degrees relative to the conservative assumption, indicating corresponding decreases of the DD SN Ia rate under the non-conservative assumption and with dynamical constraints.

### 3.3. Birth Rates of SNe Ia

The CO WDs above are used to study the SN Ia birthrates in various cases, which are finally normalized to a single starburst of $10^{11} M_{\odot}$ and a constant star formation rate of $5 M_{\odot}$ yr$^{-1}$ over the past 15 Gyr, to resemble our Galaxy. The results are shown in Figure 2. We see that, in the conservative case, the predicted SN Ia birthrate is 0.033 SNeM\footnote{1 SNeM = 1SN/(100 yr$^{-1}$)(10$^{10}$ $M_{\odot}$)$^{-1}$.} (corresponding to a Galactic birthrate of $2.5 \times 10^{-3}$ yr$^{-1}$) for the constant star formation at 15 Gyr (left panel). In the non-conservative case, the predicted overall rate is reduced to 0.019 SNeM.
We have shown that the DD model for SNe Ia is less effective than previously assumed if we consider the non-conservative nature of the DD merger process and constraints on triggering SN Ia explosions provided by recent SPH simulations. The overall SN Ia rate is reduced to a value ≈0.56–0.72 that of previous studies (or 0.018–0.024 SNe/M) by introducing the non-conservative approximation, while it is likely below 0.18 of that value (or <0.006 SNe/M) if we also consider the SPH constraints.

Theoretical estimates of the SN Ia rate from the SD model show a wide range of values from ≈0.001 SNe/M (Ruiter et al. 2009) to >0.01 SNe/M (conversing from Han & Podsiaiowski 2004; see also Mennekens et al. 2010), which strongly depends on the model assumptions and input parameters used in various studies. Wang et al. (2010) performed a study using the same synthesis model and Galactic (constant) star formation rate as used in this study, and found a rate of 0.029 SNe/M (2.15 × 10^{-3} yr^{-1}). By direct comparison, the DD model appears unlikely to be better than the SD model in explaining the SN Ia birthrate.

It was found by Pakmor et al. (2012) that an extended envelope enshrouding the merging WDs is not produced in violent merging events. However, we consider the possibility that a hot extended envelope may arise following a non-violent non-conservative DD merger. Since the disrupted material of the secondary must also contain most of the original orbital angular momentum, the outermost layers of the merger probably form a centrifugally supported disc. Our study therefore suggests that the lost or unaccreted material from the DD merger would take the form of a hot envelope plus disk, similar to that indicated by the SPH simulations of Yoon et al. (2007) in which the scale of the hot envelope is small (i.e., ≤10^{10} cm). The absence of early ultraviolet–optical emission in SN 2011fe (Nugent et al. 2011) is compatible with the DD model with a small extended envelope, while a disk would cause some continuum polarization such as that detected at red wavelengths in SN 2011fe (Smith et al. 2011), although other causes of polarization cannot be ruled out.

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