

A Single Degenerate Model for Ultra Super-Chandrasekhar Mass Progenitors of Type Ia Supernovae – Young and Low Metallicity Environments –

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Abstract. Some Type Ia supernovae (SNe Ia) are suggested to have progenitor white dwarfs (WDs) with mass of up to 2.4–2.8 M_{\odot} , highly exceeding the Chandrasekhar mass limit. We present a new single degenerate (SD) model for SNe Ia progenitors, in which the WD mass can increase by accretion up to 2.3 (2.7) M_{\odot} from the initial value of 1.1 (1.2) M_{\odot} . The results are consistent with high luminosity SNe Ia such as SN 2003fg, SN 2006gz, SN 2007if, and SN 2009dc. There are three characteristic mass ranges of exploding WDs. In an extreme massive case, differentially rotating WDs explode as a SNe Ia soon after the WD mass exceeds 2.4 M_{\odot} because of a secular instability at $T/|W| \sim 0.14$. For a mid mass range of $M_{\text{WD}} = 1.5\text{--}2.4 M_{\odot}$, which is supported by differential rotation, it takes some spinning-down time until carbon is ignited to induce an SN Ia explosion. For a lower mass range of $M_{\text{WD}} = 1.38\text{--}1.5 M_{\odot}$, they can be supported by rigid rotation until the angular momentum is lost. We also suggest the ultra super-Chandrasekhar mass SNe Ia are born in young and low metallicity environments.

Keywords. binaries: close — supernovae: individual (SN 2003fg, SN 2006gz, SN 2007if, SN 2009dc)

1. Introduction

Recent discoveries of several very bright Type Ia supernovae (SNe Ia) suggest that their progenitor white dwarfs (WDs) might have super-Chandrasekhar masses of up to 2.4–2.8 M_{\odot} (Hicken *et al.* 2007; Howell *et al.* 2006; Scalzo *et al.* 2010; Silverman *et al.* 2011; Taubenberger *et al.* 2011; Yamanaka *et al.* 2009). Super-Chandrasekhar mass of the progenitors of SNe Ia was first reported by Howell *et al.* (2006) for SN 2003fg ($\sim 2.1 M_{\odot}$ C+O WD with $1.29 \pm 0.07 M_{\odot}$ ^{56}Ni). More candidates for super-Chandrasekhar mass progenitors were added to the list, i.e., SN 2006gz, SN 2007if, and SN 2009dc. The very bright SN 2007if requires a $2.4 \pm 0.2 M_{\odot}$ progenitor C+O WD with $1.6 \pm 0.1 M_{\odot}$ ^{56}Ni (Scalzo *et al.* 2010) and SN 2009dc also demands a $\gtrsim 2.0 M_{\odot}$ progenitor C+O WD with $1.4\text{--}1.7 M_{\odot}$ ^{56}Ni (Silverman *et al.* 2011) or a $\sim 2.8 M_{\odot}$ C+O WD with $\sim 1.8 M_{\odot}$ ^{56}Ni (Taubenberger *et al.* 2011). Such a large WD mass, highly exceeding $M_{\text{Ch}} (\approx 1.4 M_{\odot})$, could challenge both the double degenerate (DD) and single degenerate (SD) scenarios. Some authors favor a DD merger scenario for these super-Chandrasekhar mass SNe Ia (e.g., Scalzo *et al.* 2010; Silverman *et al.* 2011), mainly because the existing SD scenario provides only $M_{\text{WD}} \lesssim 1.8 M_{\odot}$ (e.g., Chen & Li 2009; Liu *et al.* 2010).

In the present paper, we show that such ultra super-Chandrasekhar mass WDs with $M_{\text{WD}} > 2.0 M_{\odot}$ can be explained by the SD scenario. There are three key binary evolution processes, i.e., optically thick winds from mass-accreting WDs (Hachisu *et al.* 1996), mass-stripping from the binary companion star by the WD winds (Hachisu *et al.* 2008a), and differential rotation which makes possible a WD more massive than the Chandrasekhar limit (Yoon & Langer 2005).

2. Evolution of White Dwarf + Main-sequence Star Binaries

Figure 1 shows a binary evolution with $M_{\text{WD},0} = 1.2 M_{\odot}$, $M_{2,0} = 5.5 M_{\odot}$, $P_{\text{orb},0} = 0.57$ day (the companion fills its Roche lobe near ZAMS), and wind-stripping parameter $c_1 = 10$. When the secondary expands to fill its Roche lobe, mass transfer begins from the secondary to the WD. If the secondary is more massive than the WD, mass transfer takes place on a thermal timescale. When the mass transfer rate (a red thick solid line; a red thin solid line indicates a tenth of it) exceeds the critical rate, \dot{M}_{cr} , optically thick winds (the rate of wind mass-loss is indicated by a red dashed line) blow from the WD (see, e.g., Hachisu *et al.* 1996; Hachisu *et al.* 1999a; Hachisu *et al.* 1999b; Nomoto *et al.* 2007).

The winds from the WD collide with the secondary and strips off its surface layer (Hachisu & Kato 2003a, 2003b). This mass-stripping effect (a dash-dotted line) attenuates the mass transfer from the secondary to the WD, thus preventing the formation of a common envelope even for a rather massive secondary. Thus the mass-stripping effect widens the donor mass range of SNe Ia progenitors (Hachisu *et al.* 2008a, 2008b).

We assume that the WD is supported by differential rotation and its mass can increase without carbon being fused at the center as long as the mass accretion rate (a dotted line but overlapped by a thick solid line after $t > 10^6$ yr) is higher than $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ ($\equiv \dot{M}_b$). We assume that the WD does not grow any more when the mass-accretion rate drops below $\dot{M}_{\text{WD}} < \dot{M}_b$, because hydrogen shell-flash prevents the WD from growing.

To summarize, the mass-loss rate of the companion increases up to $-\dot{M}_2 = 1.4 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ and then quickly decreases. The optically thick wind stops at $t = 1 \times 10^6$ yr, and afterward the mass transfer rate gradually decreases to $\dot{M}_1 = \dot{M}_b = 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ at $t = 1.8 \times 10^6$ yr. The WD mass has increased to $2.7 M_{\odot}$ at this epoch.

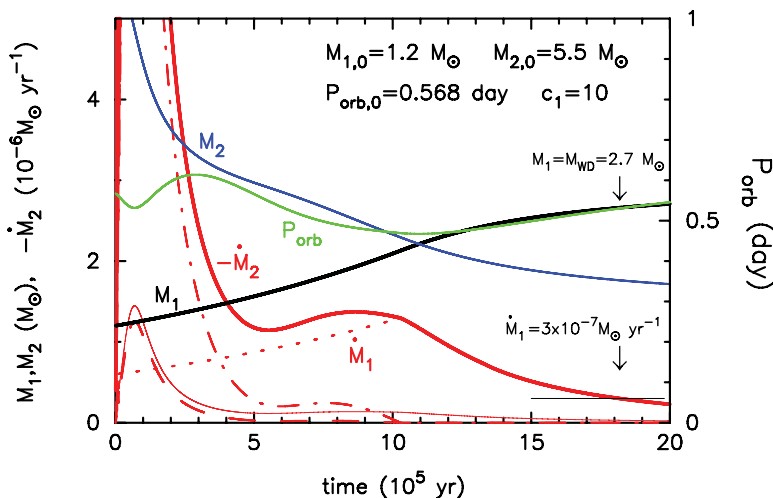


Figure 1. A binary evolution of a WD+MS pair: time starts when the mass transfer begins from the MS to the WD. The WD grows from $1.2 M_{\odot}$ to $2.7 M_{\odot}$.

3. Maximum White Dwarf Masses

We have followed binary evolutions for various sets of the initial parameters ($M_{\text{WD},0}$, $M_{2,0}$, $P_{\text{orb},0}$) and obtained maximum WD masses. Figure 2 shows the maximum WD mass $M_{\text{WD,max}}$ obtained in the binary evolution against the initial companion mass $M_{2,0}$ for various sets of parameters, $M_{\text{WD},0}$ and $P_{\text{orb},0}$. Solid lines are for the case that the companion fills its Roche lobe and begins mass-transfer to the WD near ZAMS, i.e., $P_{\text{orb},0} \sim 0.5$ day. The WD mass reaches $M_{\text{WD,max}} \approx 2.7, 2.3, 1.9, 1.7$, and $1.5 M_{\odot}$, for the initial WD mass of $M_{\text{WD},0} = 1.2, 1.1, 1.0, 0.9$, and $0.8 M_{\odot}$, respectively. Dashed lines show the case that the companion fills its Roche lobe near the end of central hydrogen burning, i.e., $P_{\text{orb},0} \sim 1.5$ day. In this case, $M_{\text{WD,max}} \approx 2.3, 2.2, 2.0, 1.8$, and $1.6 M_{\odot}$, for $M_{\text{WD},0} = 1.2, 1.1, 1.0, 0.9$, and $0.8 M_{\odot}$, respectively. These WD masses satisfy the observational requirements of super-Chandrasekhar mass SNe Ia.

These super-Chandrasekhar mass progenitors may be related to the “prompt/tardy” components of SNe Ia as shown in Figure 3. There are three characteristic mass ranges and timescales of exploding WDs depending on the secular instability and rotation law: (1) $M_{\text{WD}} > 2.4 M_{\odot}$: a secular instability sets in at $T/|W| = 0.14$ and the WD explodes as an SN Ia soon after it exceeds $2.4 M_{\odot}$. This kind of binary evolution corresponds to the very luminous super-Chandrasekhar mass SNe Ia such as SN 2007if and SN 2009dc. These brightest super-Chandrasekhar mass SNe Ia are the youngest among our models (younger than a few hundred Myr from its birth). (2) $M_{\text{WD}} = 1.5\text{--}2.4 M_{\odot}$ supported by differential rotation. (3) $M_{\text{WD}} = 1.38\text{--}1.5 M_{\odot}$ supported by rigid rotation. In the case of (2) and (3), the WD does not explode soon after the WD mass has reached the maximum mass, because the central density is low so that central carbon is not ignited yet. After some time, loss or redistribution of angular momentum would lead to an increase in the central density of the WD. This waiting time depends on the spin-down mechanism of rotating WDs (see, e.g., Ilkov & Soker 2012).

Childress *et al.* (2011) and Khan *et al.* (2011) suggested that super-Chandrasekhar mass SNe Ia are likely to appear in metal-poor environments. Our calculations show that ultra super-Chandrasekhar mass SNe Ia come preferentially from a pair of a massive C+O

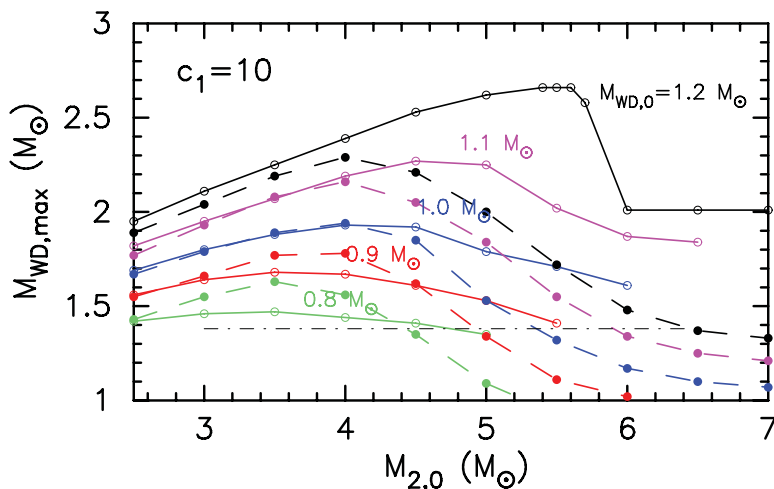


Figure 2. Maximum WD mass against the initial companion mass for the initial WD masses with various orbital periods. Solid lines: the companion slightly evolved off from ZAMS but still very close to ZAMS ($P_{\text{orb},0} \sim 0.5$ day) when the companion started mass-transfer. Dashed lines: the companion is close to the end of central hydrogen-burning ($P_{\text{orb},0} \sim 1.5$ day).

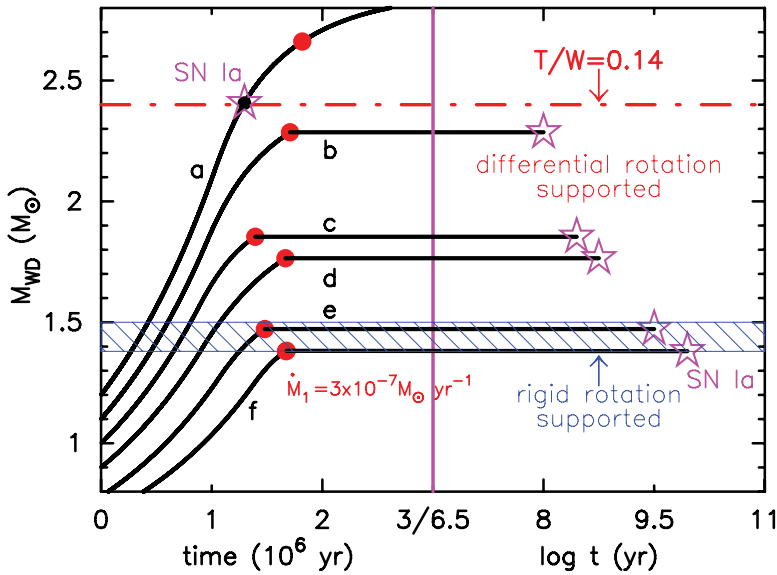


Figure 3. Schematic illustration for evolution of the WD mass against time. Time starts when the secondary fills its Roche lobe and it is switched from linear to logarithmic at $t \approx 3 \times 10^6$ yr (a vertical magenta line). The evolutionary lines on the left side of the magenta line are taken from our numerical results while those in the right side are just schematic illustrations.

WD ($\gtrsim 1.1 M_{\odot}$) and a $4 - 5 M_{\odot}$ main-sequence star, which indicates a rather young population (several hundred Myr or so). Massive initial C+O WDs ($\sim 1.1 - 1.2 M_{\odot}$) are born in low metallicity environments because the AGB wind (or superwind) is relatively weak so that the C+O WD can grow up to $\sim 1.2 M_{\odot}$ before the first common envelope evolution. See Hachisu *et al.* (2012) for more details.

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