

## ON THE PROGENITORS OF SUPER-CHANDRASEKHAR MASS TYPE Ia SUPERNOVAE

WEN-CONG CHEN<sup>1</sup> AND XIANG-DONG LI<sup>2</sup>

<sup>1</sup> Department of Physics, Shangqiu Normal University, Shangqiu 476000, China; [chenwc@nju.edu.cn](mailto:chenwc@nju.edu.cn)

<sup>2</sup> Department of Astronomy, Nanjing University, Nanjing 210093, China; [lixd@nju.edu.cn](mailto:lixd@nju.edu.cn)

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### ABSTRACT

Type Ia supernovae (SNe Ia) can be used as the standard candle to determine the cosmological distances because they are thought to have a uniform fuel amount. Recent observations of several overluminous SNe Ia suggest that the white dwarf masses at supernova explosion may significantly exceed the canonical Chandrasekhar mass limit. These massive white dwarfs may be supported by rapid differential rotation. Based on a single-degenerate model and the assumption that the white dwarf would differentially rotate when the accretion rate  $\dot{M} > 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ , we have calculated the evolutions of close binaries consisting of a white dwarf and a normal companion. To include the effect of rotation, we introduce an effective mass  $M_{\text{eff}}$  for white dwarfs. For the donor stars with two different metallicities  $Z = 0.02$  and  $0.001$ , we present the distribution of the initial donor star masses and the orbital periods of the progenitors of super-Chandrasekhar mass SNe Ia. The calculation results indicate that, for an initial massive white dwarf of  $1.2 M_{\odot}$ , a considerable fraction of SNe Ia may result from super-Chandrasekhar mass white dwarfs, but very massive ( $> 1.7 M_{\odot}$ ) white dwarfs are difficult to form, and none of them could be found in old populations. However, super-Chandrasekhar mass SNe Ia are very rare when the initial mass of white dwarfs is  $1.0 M_{\odot}$ . Additionally, SNe Ia in low metallicity environment are more likely to be homogeneous.

*Key words:* binaries: close – stars: evolution – supernovae: general – white dwarfs

### 1. INTRODUCTION

Type Ia supernovae (SNe Ia) are generally believed to be thermonuclear explosions of accreting carbon–oxygen white dwarfs (Hoyle & Fowler 1960) when their masses reach the Chandrasekhar mass of  $\sim 1.4 M_{\odot}$  (Chandrasekhar 1931). Due to this uniform progenitor mass (Mazzali et al. 2007), most SNe Ia present a good correlation between the peak brightness and the width of the light curve (Phillips 1993), so it is possible to use them as the standard candle to determine the cosmological distances (Riess et al. 1998, 2004; Perlmutter et al. 1999).

There exist double-degenerate model (Iben & Tutukov 1984; Webbink 1984) and single-degenerate model (Whelan & Iben 1973; Nomoto 1982) for the progenitors of SNe Ia (for a review, see Branch et al. 1995). Based on the single-degenerate model, the evolutions of binary systems consisting of an accreting white dwarf have been widely explored by many authors (Hachisu et al. 1996, 1999b, 1999a, 2008; Li & van den Heuvel 1997; Yoon & Langer 2003; Han & Podsiadlowski 2004; Chen & Li 2007; Meng et al. 2009; Xu & Li 2009; Han 2008; Wang et al. 2009).

The supernova SNLS-03D3bb (2003fg) was discovered on 2003 April 24, and observed to be 2.2 times overluminous than a normal SN Ia (Astier et al. 2006). Howell et al. (2006) inferred the mass of  $^{56}\text{Ni}$   $\sim 1.3 M_{\odot}$ , which indicates that the mass of the white dwarf at the moment of explosion is  $\sim 2.1 M_{\odot}$ .<sup>3</sup> Wang et al. (2008) also suggested white dwarfs with super-Chandrasekhar masses as the progenitors of some rare nickel-rich SNe Ia ( $M_{\text{Ni}} > 0.8 M_{\odot}$ ). These massive white dwarfs may be supported by rapid rotation (Yoon & Langer 2005), or origin from the merger of two massive white dwarfs (Tutukov & Yungelson 1994; Howell 2001). More recently, two other

possibly overluminous SNe Ia: SN 2006gz (Hicken et al. 2007) and SN 2007if (Yuan et al. 2007) were reported.

It is interesting to explore the properties of the progenitors of overluminous SNe Ia like SNLS-03D3bb in the single-degenerate model. Recently, some authors have taken account of the influence of rotation on the accreting white dwarf in their works (Uenishi et al. 2003; Saio & Nomoto 2004; Yoon & Langer 2004, 2005). Yoon & Langer (2004) found that a white dwarf with the accretion rate of  $\gtrsim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$  may rotate differentially. The maximum equilibrium mass for a secularly stable white dwarf with differential rotation is given by (Shapiro & Teukolsky 1983)

$$M_{\text{max}} \approx 2.5 \left( \frac{2}{\mu_e} \right)^2 M_{\odot}, \quad (1)$$

where  $\mu_e$  is the mean molecular weight per electron. This value is in line with the results derived by Durisen (1975) and Durisen & Imamura (1981) via detailed numerical calculations.

Considering the angular momentum transfer by mass accretion, Yoon et al. (2004) simulated the evolution of helium-accreting CO white dwarfs for different mass accretion rate, and found that the rotation can help white dwarfs grow in mass by stabilizing helium shell burning. Based on the rigidly rotating progenitor model, Domínguez et al. (2006) computed the evolution of a rotating CO white dwarf accreting CO-rich matter. Their results show that more massive progenitors result in higher  $^{56}\text{Ni}$  mass and explosive luminosity, and more massive white dwarfs at explosion.

Assuming that overluminous SNe Ia originate from binary systems consisting of an accreting white dwarf with super-Chandrasekhar mass, in this paper we investigate the distribution of the initial donor star mass and orbital period of the progenitor binaries. In Section 2, we describe the input physics in stellar and binary evolution calculations. Numerically calculated results for the evolutionary sequences of white dwarf binaries are presented in Section 3. In Section 4, we summarize the results with a brief discussion on the limitation of this study.

<sup>3</sup> Hillebrandt et al. (2007) suggested an alternative model to account for the high brightness of SNLS-03D3bb, in which an off-center ignition of nuclear burning in a Chandrasekhar mass white dwarf occurs and drives a lopsided explosion.

## 2. INPUT PHYSICS

In this work, we study the evolution of close binaries consisting a CO white dwarf (of mass  $M_{\text{wd}}$ ) and a normal companion (of mass  $M_{\text{d}}$ ) with Population I and II metallicities ( $Z = 0.02$  and  $0.001$ , respectively). The white dwarf binary results from a binary consisting of two main-sequence stars, in which the more massive star evolves more rapidly, and becomes the CO white dwarf. With nuclear evolution, the secondary star starts to fill its Roche lobe and transfer hydrogen-rich material to the white dwarf. Our calculations begin at this stage.

The accreted material on the white dwarf will be heated and compressed, finally leading to nuclear burning. If the burning process is unstable, part of the mass is ejected from the white dwarf. The accumulated efficiencies for hydrogen and helium burning are denoted as  $\alpha_{\text{H}}$  and  $\alpha_{\text{He}}$ , respectively. Although calculations of  $\alpha_{\text{H}}$  and  $\alpha_{\text{He}}$  have been done by, e.g., Kovetz & Prialnik (1994) and Kato & Hachisu (2004), they are limited to nonrotating white dwarfs, and in principle, inadequate to determine the final mass of H accreting rotating white dwarfs. To explore the effect of stellar rotation on the thermal response of accreting CO white dwarfs, we include the lifting effect in the hydrostatic equilibrium according to the prescriptions in Domínguez et al. (1996), and introduce an effective mass  $M_{\text{eff}}$  of the white dwarf by taking account of the centrifugal force. We then adopt the corresponding values of  $\alpha_{\text{H}}$  and  $\alpha_{\text{He}}$  for this effective mass from the formulae in Han & Podsiadlowski (2004) and Kato & Hachisu (2004). The method can be described as follows. We divide the surface of the white dwarf into three zones with different ranges of the polar angle: the equatorial zone ( $\theta = 60^\circ\text{--}120^\circ$ ), the middle zone ( $\theta = 30^\circ\text{--}60^\circ$  and  $120^\circ\text{--}150^\circ$ ), and the polar zone ( $\theta = 0^\circ\text{--}30^\circ$  and  $150^\circ\text{--}180^\circ$ ). Assuming rigid body rotation and neglecting any deformation of the white dwarf, the effective mass  $M_{\text{eff}}$  of the white dwarf in the zone with the polar angles between  $\theta_1$  and  $\theta_2$  satisfies

$$\frac{GM_{\text{eff}}}{R^2} = \frac{GM_{\text{wd}}}{R^2} - \frac{\int_{\theta_1}^{\theta_2} 2\pi\omega^2 R^3 \sin^3\theta d\theta}{\int_{\theta_1}^{\theta_2} 2\pi R^2 \sin\theta d\theta}, \quad (2)$$

where  $R$  and  $\omega$  are the radius and angular velocity of the white dwarf, respectively. In Equation (2), the radial component of the centrifugal force is averaged by an area-weighted mean.

We further assume that each zone accretes the transferred material at a rate proportional to its area, i.e., its accretion fraction  $f_i = \int_{\theta_1}^{\theta_2} 2\pi R^2 \sin\theta d\theta / 4\pi R^2$ , and  $f_i = 0.5, 0.366$ , and  $0.134$  for the equatorial, middle, and polar zones, respectively. Replacing  $M_{\text{wd}}$  with  $M_{\text{eff}}$ , we can simply obtain the H- and He-accumulated efficiencies ( $\alpha_{\text{H},i}$  and  $\alpha_{\text{He},i}$ ) for different zones on the surface of the white dwarf. Summarizing the above prescriptions, the mass growth rate of the white dwarf can then be written as

$$\dot{M}_{\text{wd}} = \sum \alpha_{\text{H},i} \alpha_{\text{He},i} f_i \dot{M}_{\text{d}}, \quad (3)$$

where  $\dot{M}_{\text{d}}$  is the mass transfer rate from the donor star.

We also calculate the spin evolution of the white dwarf, neglecting the possible interaction between the magnetic field of the white dwarf and the accretion disk. The rotation of the white dwarf may be related to the rotation of its progenitor star (Heger & Langer 2000; Maeder & Meynet 2000), but is more likely to be attained during mass transfer, as the transferred material from the donor star carries a large amount of angular momentum, which can cause spin-up of the white dwarf (Durisen 1977;

Ritter 1985; Narayan & Pophm 1989; Langer et al. 2000). Generally, the white dwarf will spin up along with accretion from a disk (Durisen 1977; Ritter 1985). When the rotation of the white dwarf is close to break-up, numerical calculations showed that angular momentum will be transferred from the white dwarf into the accretion disk, and the rotation velocity will roughly keep constant (Paczyński 1991; Popham & Narayan 1991). Hence, we set the specific angular momentum of the effective accreted matter to be

$$j_{\text{acc}} = \begin{cases} \sqrt{GM_{\text{wd}}R}, & v < 0.9v_{\text{K}}, \\ 0, & v \geq 0.9v_{\text{K}}, \end{cases} \quad (4)$$

where  $v = \omega R$ , and  $v_{\text{K}} = \sqrt{GM_{\text{wd}}/R}$  are the rotation velocity and the Keplerian velocity at the white dwarf's equator, respectively. In our calculations, the initial surface velocity at the white dwarf's equator is taken to be  $10 \text{ km s}^{-1}$ , and the white dwarf radius changes with  $R \propto M_{\text{wd}}^{-1/3}$ .

The losses of mass and orbital angular momentum play an important role in the mass transfer and orbital evolution of close binary systems. The mass loss rate of the binary system is  $\dot{M} = (1 - \sum \alpha_{\text{H},i} \alpha_{\text{He},i} f_i) \dot{M}_{\text{d}}$ , and we assume that this mass is ejected in the vicinity of the white dwarf in the form of isotropic winds or outflows, taking away the specific orbital angular momentum of the white dwarf. The rate of orbital angular momentum loss through mass loss is given by

$$\dot{J}_{\text{is}} = \left(1 - \sum \alpha_{\text{H},i} \alpha_{\text{He},i} f_i\right) \frac{\dot{M}_{\text{d}} M_{\text{d}}}{M M_{\text{wd}}} J, \quad (5)$$

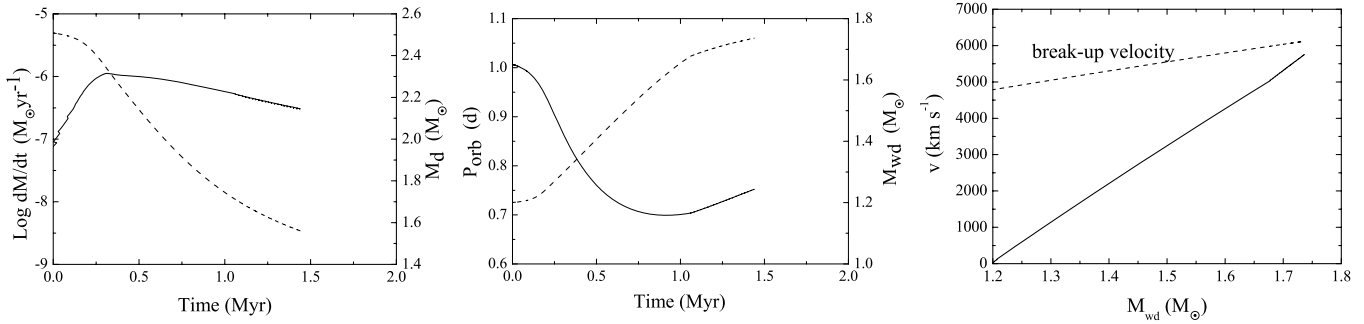
where  $J = (M_{\text{d}} M_{\text{wd}} / M) a^2 \Omega$ ,  $M = M_{\text{d}} + M_{\text{wd}}$ , and  $\Omega$  are the orbital angular momentum, total mass, and orbital angular velocity of the binary system, respectively.

With numerical simulations, Yoon & Langer (2004) found that, accreting at a rate  $\gtrsim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ , a white dwarf would rotate differentially, and there would not be the central carbon ignition even if its mass exceed  $1.4 M_{\odot}$ . As a result of the differential rotation, a white dwarf with a super-Chandrasekhar mass may exist. Accordingly, we assume that a SN Ia occurs when  $M_{\text{wd}} \geq 1.4 M_{\odot}$  and  $\dot{M} < 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ , so that there is no differential rotation to support the massive white dwarf. In the case of  $M_{\text{wd}} > 1.4 M_{\odot}$  and  $\dot{M} > 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ , we let the white dwarf increase mass up to  $M_{\text{max}}$ .

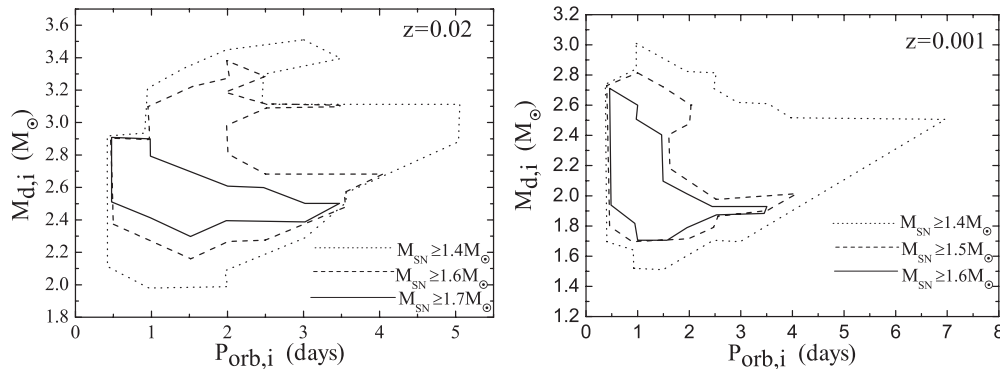
## 3. RESULTS

We have calculated the evolution of white dwarf binaries adopting an updated version of the stellar evolution code developed by (Eggleton 1971, 1972; see also Han et al. 1994; Pols et al. 1995). The stellar OPAL opacities are from Rogers & Iglesias (1992), and Alexander & Ferguson (1994) for a low temperatures. In the calculations, we take the ratio of the mixing length to the pressure scale height to be 2.0. The evolutionary results are determined by three parameters of white dwarf binaries: the initial mass of the white dwarf  $M_{\text{wd},i}$  (taken to be  $1.2 M_{\odot}$  and  $1.0 M_{\odot}$ ), the initial mass of the donor star  $M_{\text{d},i}$ , and the initial orbital period of binary systems  $P_{\text{orb},i}$ .

We first present an example of the evolutionary sequences for a binary system with  $M_{\text{wd},i} = 1.2 M_{\odot}$ ,  $M_{\text{d},i} = 2.5 M_{\odot}$ , and  $P_{\text{orb},i} = 1.0$  day, in which the donor star has a solar composition ( $Y = 0.28$ ,  $Z = 0.02$ ). In Figure 1, we plot the evolution of the mass transfer rate and the donor star mass with time in the left panel, the evolution of the orbital period and the white dwarf mass in the middle panel, and the evolution of rotation velocity



**Figure 1.** Evolution of a white dwarf binary with  $M_{\text{wd},i} = 1.2 M_{\odot}$ ,  $M_{\text{d},i} = 2.5 M_{\odot}$  and  $P_{\text{orb},i} = 1.0$  day. The solid and dashed curves denote the evolutionary tracks of the mass transfer rate and the donor star mass in the left panel, the orbital period and the white dwarf mass in the middle panel, and the rotation velocity and break-up velocity at the white dwarf's equator in the right panel, respectively.



**Figure 2.** Distribution of the initial orbital periods  $P_{\text{orb},i}$  and the initial donor star masses  $M_{\text{d},i}$  of the progenitor systems of super-Chandrasekhar mass SNe Ia when  $M_{\text{wd},i} = 1.2 M_{\odot}$ . The left and right panels are for  $Z = 0.02$  and  $0.001$ , respectively.

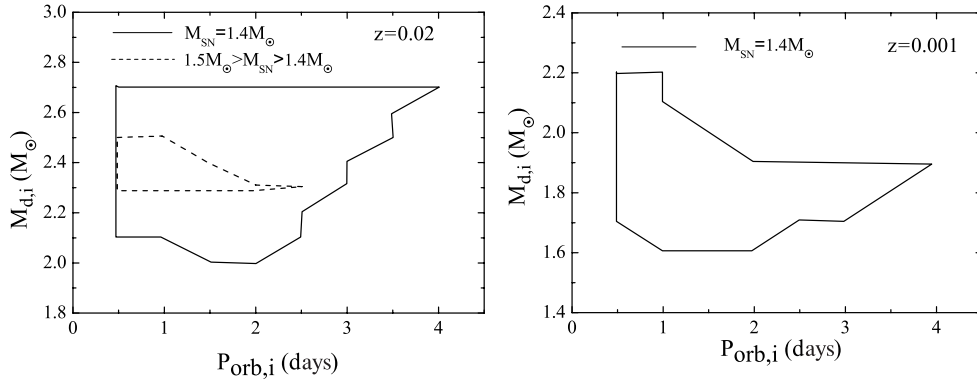
at the white dwarf's equator in the right panel. The donor star fills its Roche lobe when its age is  $\sim 3.84 \times 10^8$  yr. Because of a relatively high initial mass ratio, the mass transfer occurs on a thermal timescale at a high rate of  $\sim 10^{-7}$ – $10^{-6} M_{\odot} \text{ yr}^{-1}$ , but remains stable due to strong isotropic wind from the white dwarf. After  $\sim 1.5$  Myr mass transfer, the white dwarf grows to  $1.75 M_{\odot}$ , and trigger a type Ia supernova when the mass transfer rate  $\dot{M}$  declines to be  $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ . The orbital period firstly decreases to 0.7 day, because material is transferred from the more massive donor star to the less massive white dwarf, and then increases when the white dwarf mass grows and exceeds the donor star mass. With gaining spin angular momentum from the accretion material, the rotation velocity of the white dwarf gradually increases and reaches near the break-up velocity.

To investigate the distribution of the initial donor star mass and orbital period for the progenitor systems of super-Chandrasekhar mass SNe Ia, we have calculated the evolutions of a large number of white dwarf binaries with different values of  $M_{\text{d},i}$  and  $P_{\text{orb},i}$  when  $M_{\text{wd},i} = 1.2 M_{\odot}$ . Figure 2 summarizes our calculated results in the  $M_{\text{d},i}$ – $P_{\text{orb},i}$  plane with  $Z = 0.02$  (left panel) and  $0.001$  (right panel), respectively. In the case of  $Z = 0.02$ , the regions enclosed by the solid, dashed, and dotted curves denote the distribution areas of initial white dwarf binaries with  $M_{\text{SN}} \geq 1.7 M_{\odot}$ ,  $\geq 1.6 M_{\odot}$ , and  $\geq 1.4 M_{\odot}$ , respectively. Beyond these areas, SNe Ia cannot occur due to either a low mass accumulation efficiency of the white dwarf or unstable mass transfer. In the case of  $Z = 0.001$ , the solid, dashed, and dotted curves correspond to the boundaries of the distribution area for the progenitors with  $M_{\text{SN}} \geq 1.6 M_{\odot}$ ,  $\geq 1.5 M_{\odot}$ , and  $\geq 1.4 M_{\odot}$ , respectively, and we cannot find that a white dwarf mass exceeds  $1.7 M_{\odot}$ . When the metallicity  $Z$  changes

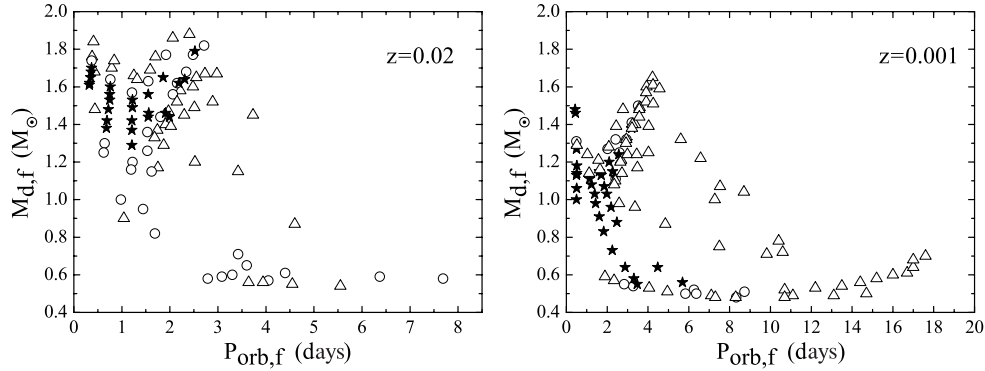
from 0.02 to 0.001, the occupied region by the progenitors of SNe Ia has a tendency to move downward in the  $M_{\text{d},i}$ – $P_{\text{orb},i}$  diagram, i.e., the progenitors with a higher  $Z$  tend to have a more massive donor star in agreement with Meng et al. (2009). However, it is difficult to produce a super-Chandrasekhar mass SN Ia when the donor mass is as low as  $1.0 M_{\odot}$ . Figure 3 presents the progenitor distribution of SNe Ia in the  $M_{\text{d},i}$ – $P_{\text{orb},i}$  plane when  $M_{\text{wd},i} = 1.0 M_{\odot}$ . For  $Z = 0.02$ , the maximum explosion mass of white dwarfs is always less than  $1.5 M_{\odot}$ .

Figure 4 shows the distribution of  $M_{\text{d},f}$  and  $P_{\text{orb},f}$  at the moment of SN explosion. The open triangles, open circles, and solid stars denote systems with  $1.6 M_{\odot} > M_{\text{SN}} \geq 1.4 M_{\odot}$ ,  $1.7 M_{\odot} > M_{\text{SN}} \geq 1.6 M_{\odot}$ , and  $M_{\text{SN}} \geq 1.7 M_{\odot}$  in the left panel ( $Z = 0.02$ ), and  $1.5 M_{\odot} > M_{\text{SN}} \geq 1.4 M_{\odot}$ ,  $1.6 M_{\odot} > M_{\text{SN}} \geq 1.5 M_{\odot}$ , and  $M_{\text{SN}} \geq 1.6 M_{\odot}$  in the right panel ( $Z = 0.001$ ), respectively. For  $Z = 0.02$  and  $M_{\text{SN}} \geq 1.7 M_{\odot}$ , the companion masses  $\sim 1.3$ – $1.8 M_{\odot}$  and orbital periods  $\sim 0.4$ – $2.0$  days, while in the case of  $Z = 0.001$  and  $M_{\text{SN}} \geq 1.6 M_{\odot}$ , the companion masses  $\sim 0.5$ – $1.5 M_{\odot}$  and orbital periods  $\sim 0.4$ – $6.0$  days. In Figure 5, we plot the distribution of the companion stars at the moment of SNe Ia in the H–R diagram. They have luminosities in the range of  $\sim 1.0$ – $10 L_{\odot}$  and effective temperatures in the range of  $\sim 5000$ – $6000$  K. These properties may be compared with and testified by future optical observations of SN Ia remnants.

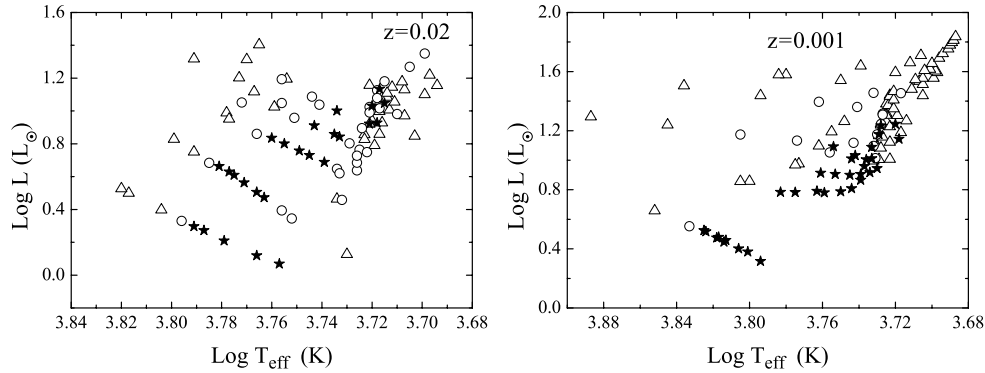
Certainly our approach in estimating the mass accumulation efficiency on rotating white dwarfs is very rough and simplified. We only consider the effect of centrifugal force and neglect the thermal and chemical evolutions on the surface of rapid rotating white dwarfs, which is very complicated. In our calculations, we assumed a rigid rotation instead of a differential rotation, which only increases slightly the Chandrasekhar limit to be  $1.48 M_{\odot}$



**Figure 3.** Distribution of the initial orbital periods  $P_{\text{orb},i}$  and the initial donor star masses  $M_{d,i}$  of the progenitor systems of SNe Ia when  $M_{\text{wd},i} = 1.0 M_{\odot}$ . The left and right panels are for  $Z = 0.02$  and  $0.001$ , respectively.



**Figure 4.** Donor star masses  $M_{d,f}$  vs. the orbital periods  $P_{\text{orb},f}$  when SN Ia explosions occur. Left ( $Z = 0.02$ ): the open triangles, open circles, and solid stars denote systems with  $1.6 M_{\odot} > M_{\text{SN}} \geq 1.4 M_{\odot}$ ,  $1.7 M_{\odot} > M_{\text{SN}} \geq 1.6 M_{\odot}$ , and  $M_{\text{SN}} \geq 1.7 M_{\odot}$ , respectively. Right ( $Z = 0.001$ ): the open triangles, open circles, and solid stars denote systems with  $1.5 M_{\odot} > M_{\text{SN}} \geq 1.4 M_{\odot}$ ,  $1.6 M_{\odot} > M_{\text{SN}} \geq 1.5 M_{\odot}$ , and  $M_{\text{SN}} \geq 1.6 M_{\odot}$ , respectively.



**Figure 5.** Distribution of the donor stars in the H–R diagram when SN Ia explosions occur. Symbols are the same as in Figure 4.

(Yoon & Langer 2004). Additionally, the white dwarf will be deformed during spin-up, not obeying spherical symmetry as we assumed. Nevertheless, our results show that the mass accumulation efficiency of white dwarfs decreases with rotation. This is at least qualitatively consistent with Piersanti et al. (2003), in which the authors compared rigidly rotating white dwarfs with nonrotating objects for CO accretion at various accretion rates, and found that an increase in the angular velocity of the white dwarf always leads to a decrease in the value of the accretion rate below which central carbon ignition will occur. The reason is that including rotation causes the accreting star to be both less dense and cooler, resulting in a larger thermal diffusion timescale, while the effect of compression induced by the accretion process is only slightly modified. This implies that our treatment might not be far from real situations.

The influence of metallicities on the mass accumulation efficiency can be found in Figure 6, which shows the fraction of

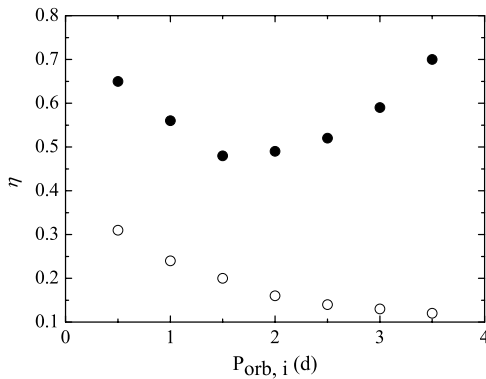
mass growth in the transferred mass

$$\eta = \frac{M_{\text{wd},f} - M_{\text{wd},i}}{M_{d,i} - M_{d,f}} \quad (6)$$

against the initial orbital period  $P_{\text{orb},i}$  when the initial mass of the donor star  $M_{d,i} = 2.5 M_{\odot}$ . It is clearly seen that, for the same donor star, white dwarfs accompanied by a Population I star have a higher mass growth rate.

#### 4. DISCUSSION AND SUMMARY

Recently discovered overluminous SNe Ia suggested that they might have originated from super-Chandrasekhar mass white dwarfs (Howell et al. 2006; Hicken et al. 2007; Yuan et al. 2007). Based on the single-degenerate model and the suggestion that massive white dwarfs might be supported by rapid differential rotation when the accretion rate  $\dot{M} \gtrsim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$



**Figure 6.** Parameters  $\eta$  vs. the initial orbital periods  $P_{\text{orb},i}$  when the initial masses of donor stars  $M_{\text{d},i} = 2.5 M_{\odot}$ . The filled circles and open circles correspond to the calculated results for  $Z = 0.02$  and  $0.001$ , respectively.

(Ostriker 1966; Ostriker & Bodenheimer 1968; Ostriker & Tassoul 1969; Durisen 1975; Shapiro & Teukolsky 1983; Yoon & Langer 2005), we have performed numerical calculations of the evolution of white dwarf binaries to investigate the properties of the progenitor of super-Chandrasekhar mass SNe Ia. The results can be summarized as follows.

1. For white dwarfs with an initial mass of  $\lesssim 1.0 M_{\odot}$ , the explosion masses of SNe Ia are nearly uniform, i.e., super-Chandrasekhar mass SNe Ia are difficult to produce. This is consistent with the rareness of super-Chandrasekhar mass SNe Ia in observations.
2. When  $M_{\text{wd},i} = 1.2 M_{\odot}$ , depending on the evolutionary paths the masses ( $M_{\text{SN}}$ ) of exploding white dwarfs range from  $1.4 M_{\odot}$  to  $1.76 M_{\odot}$ . A considerable fraction of SNe Ia are of super-Chandrasekhar mass, suggesting a diversity in the brightness of SNe Ia. However, in most cases the final masses of the white dwarfs are not significantly exceeding  $1.4 M_{\odot}$ , and it is very difficult to produce a SN Ia with  $M_{\text{SN}} \gtrsim 1.8 M_{\odot}$ . Thus, our model cannot reproduce an overluminous SN Ia with  $M_{\text{SN}} \gtrsim 2.0 M_{\odot}$  like SNLS-03D3bb (Howell et al. 2006).<sup>4</sup>
3. Progenitors of super-Chandrasekhar mass ( $M_{\text{SN}} \geq 1.6 M_{\odot}$ ) SNe Ia can be constrained to be white dwarf (with the initial mass of  $1.2 M_{\odot}$ ) binaries with an initial donor star mass of  $M_{\text{d},i} \sim 2.2\text{--}3.3 M_{\odot}$  and an initial orbital period of  $P_{\text{orb},i} \sim 0.5\text{--}4.0$  days when  $Z = 0.02$ , and  $M_{\text{d},i} \sim 1.7\text{--}2.7 M_{\odot}$  and  $P_{\text{orb},i} \sim 0.5\text{--}3.5$  days when  $Z = 0.001$ . Interestingly, it is not those binaries with most massive donors that are more likely to evolve to super-Chandrasekhar mass SNe Ia, since the mass transfer rates in these systems usually decline rapidly below  $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ , so that the white dwarf does not have sufficient time to accrete. The time delay between the formation of the progenitor systems and the explosions of SNe Ia is  $\lesssim 1$  Gyr, in agreement with the suggestion that super-Chandrasekhar mass SNe Ia should be more likely to exist in a young stellar population (Howell et al. 2006), but they do not seem to belong to the youngest population. Especially, one would not expect overluminous SNe Ia in early-type galaxies.
4. Metallicities have important influence on the production of super-Chandrasekhar mass SNe Ia. Systems with Population II donor stars are less likely to be the progenitor of SN

<sup>4</sup> It is controversial if the progenitor of SN 2003fg is a super-Chandrasekhar mass white dwarf. Based on the low velocity and short timescale seen in SN 2003fg, Maeda & Iwamoto (2009) suggested that its ejecta mass is smaller than  $1.4 M_{\odot}$ .

Ia with a super-Chandrasekhar mass of  $\gtrsim 1.7 M_{\odot}$ , suggesting that SNe Ia at relatively high redshifts might be more homogeneous than nearby ones.

Perhaps the biggest issue in this work is how super-Chandrasekhar mass white dwarfs can be formed and related to overluminous SNe Ia. The nature of the overluminous SNe Ia is not yet well understood. For example, Subaru and Keck optical spectroscopic and photometric observations of SN Ia 2006gz show that the late-time behavior of this SN is distinctly different from that of normal SNe Ia, but the peculiar features found at late times (the SN is faint and it lacks [Fe II] and [Fe III] emission) are not readily connected to a large amount of  $^{56}\text{Ni}$  (Maeda et al. 2009). Even if super-Chandrasekhar mass white dwarfs do exist in the universe, their formation path is poorly known. In principle, both the merging of a close binary system of two massive white dwarfs and accretion onto a normal white dwarf may form a rapidly spinning white dwarf that considerably exceeds the Chandrasekhar limit, provided that they rotate differentially. In the latter case, under what circumstances can a differentially rotating white dwarf be sustained has not been well addressed. We have adopted the simple criterion of the mass accretion rate, but the real situation should be sensitively dependent on the efficiency of mass and angular momentum gain and loss during mass transfer, which may also be related to the magnetic field strength of the white dwarfs.

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