The helium star donor channel for the progenitors of Type Ia supernovae

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Accepted 2009 January 22. Received 2009 January 8; in original form 2008 November 5

ABSTRACT

Type Ia supernovae (SNe Ia) play an important role in astrophysics, especially in the study of cosmic evolution. Several progenitor models for SNe Ia have been proposed in the past. In this paper we carry out a detailed study of the He star donor channel, in which a carbon–oxygen white dwarf (CO WD) accretes material from a He main-sequence star or a He subgiant to increase its mass to the Chandrasekhar mass. Employing Eggleton’s stellar evolution code with an optically thick wind assumption, and adopting the prescription of Kato & Hachisu for the mass accumulation efficiency of the He-shell flashes on to the WDs, we performed binary evolution calculations for about 2600 close WD binary systems. According to these calculations, we mapped out the initial parameters for SNe Ia in the orbital period–secondary mass (log $P^i$ – $M^i_2$) plane for various WD masses from this channel. The study shows that the He star donor channel is noteworthy for producing SNe Ia ($\sim 1.2 \times 10^{-3}$ yr$^{-1}$ in our Galaxy), and that the progenitors from this channel may appear as supersoft X-ray sources. Importantly, this channel can explain SNe Ia with short delay times ($\lesssim 10^3$ yr), which is consistent with the recent observational implications of young populations of SN Ia progenitors.

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

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are excellent cosmological distance indicators owing to their high luminosities and remarkable uniformity. They have been applied successfully to the task of determining cosmological parameters (e.g. $\Omega$ and $A$: Riess et al. 1998; Perlmutter et al. 1999). It is widely believed that SNe Ia are thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) accreting matter from their companions (see the review of Nomoto, Iwamoto & Kishimoto 1997). However, several key issues related to the nature of their progenitor systems and the physics of the explosion mechanisms are still not well understood (Hillebrandt & Niemeyer 2000; Röpke & Hillebrandt 2005; Wang et al. 2008; Podsiadlowski et al. 2008), which may raise doubts about the distance calibration being purely empirical and on the basis of the SN Ia sample of the low-redshift Universe.

At present, two SN Ia explosion models are frequently discussed, that is the Chandrasekhar (Ch) mass model and the sub-Chandrasekhar (sub-Ch) mass model. The synthetic spectra of the Ch mass model are in excellent agreement with the early time spectra of most SNe Ia, while those of the sub-Ch mass model have difficulty in matching observations (Höflich & Khokhlov 1996). A CO WD can increase its mass to the Ch mass through a single-degenerate (SD) scenario, where the CO WD accretes H/He-rich material from a non-degenerate companion star (Whelan & Iben 1973; Nomoto, Thielemann & Yokoi 1984), or through a double-degenerate (DD) scenario, where another CO WD merges with it and the total mass of the two CO WDs is larger than the Ch mass limit (Iben & Tutukov 1984; Webbink 1984). Theoretically, it is suggested that the DD scenario likely leads to an accretion-induced collapse rather than a SN Ia (Nomoto & Iben 1985; Saio & Nomoto 1985; Timmes, Woosley & Taam 1994).

For the SD Ch scenario, the companion is probably a main-sequence (MS) star or a slightly evolved subgiant star (WD + MS channel), or a red giant star (WD + RG channel) (Hachisu, Kato & Nomoto 1996; Hachisu et al. 1999a; Hachisu, Kato & Nomoto 1999b; Li & van den Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004, 2006; Chen & Li 2007; Han 2008; Meng, Chen & Han 2009). Meanwhile, a CO WD may also accrete material from a He star companion to increase its mass to the Ch mass, a process known as the He star donor channel in this paper. The study of Iben & Tutukov (1994) showed that WD + He star systems can be formed via binary evolution. Yoon & Langer (2003) have carried out the evolution of a CO WD + He star system with a $1.0 M_\odot$ CO WD and a $1.6 M_\odot$ He star in a 0.124 d orbit. In this binary, the WD accretes He from the He star and grows in mass to the Ch mass. It is believed that WD + He star systems generally originate from intermediate-mass binary systems. Thus, this channel may explain SNe Ia with short delay times (Mannucci, Della Valle &
2 BINARY EVOLUTION CALCULATIONS

In WD + He star systems, the He star fills its Roche lobe at the He MS or He subgiant stage, and then mass transfer begins. The He star transfers some of its material on to the surface of the WD, which increases the mass of the WD as a consequence. If the WD grows to 1.378M⊙, we assume that the WD explodes as a SN Ia. Here we use Eggleton’s stellar evolution code (Eggleton 1971, 1972, 1973) to calculate the binary evolution of WD + He star systems. The code has been updated with the latest input physics over the last three decades (Han, Podsiałowski & Eggleton 1994; Pols et al. 1995, 1998). Roche-lobe overflow (RLOF) is treated within the code described by Han, Tout & Eggleton (2000). We set the ratio of mixing length to local pressure scaleheight, ɑ = 1/Hp, to be 2.0. The opacity tables are compiled by Chen & Tout (2007) from Eggleston & Rogers (1996) and Alexander & Ferguson (1994). In our calculations, the He star models are composed of He abundance Y = 0.98 and metallicity Z = 0.02, and all calculations for the He stars are carried out without enhanced mixing (i.e. the overshooting parameter, δov, is taken to be zero; see Dewi et al. 2002). In addition, orbital angular momentum loss due to gravitational wave radiation (GWR) is included by adopting a standard formula presented by Landau & Lifshitz (1971):

$$\frac{d \log J_{GR}}{dt} = -\frac{32G^{3}}{5c^{5}} \frac{M_{WD}M_{2}(M_{WD} + M_{2})}{a^{3}}$$

(1)

where G, c, MWD and M2 are the gravitational constant, constant, vacuum speed of light, mass of the accreting WD and mass of the companion He star, respectively.

Instead of solving the stellar structure equations of a WD, we use an optically thick wind model (Kato & Hachisu 1994; Hachisu et al. 1996) and adopt the prescription of Kato & Hachisu (2004, hereafter KH04) for the mass accumulation efficiency of He-flash shells on to the WD. If the mass transfer rate, \(\dot{M}_{2}\), is above a critical rate, \(\dot{M}_{cr}\), we assume that He burns steadily on the surface of the WD and that the He-rich matter is converted into C and O at a rate \(\dot{M}_{cr}\). The unprocessed matter is lost from the system, presumably in the form of an optically thick wind at a mass loss rate \(\dot{M}_{wind} = |\dot{M}_{2}| - \dot{M}_{cr}\).

The critical mass transfer rate is

\[ \dot{M}_{cr} = 7.2 \times 10^{-6}(M_{WD}/M_{\odot} - 0.6)M_{\odot}\text{yr}^{-1}, \]

based on WD models computed with constant mass accretion rates (Nomoto 1982).

The following assumptions are adopted when \(|\dot{M}_{2}|\) is smaller than \(\dot{M}_{cr}\):

1. If \(|\dot{M}_{2}|\) is less than \(\dot{M}_{cr}\) but higher than the minimum accretion rate of stable He-shell burning, \(\dot{M}_{H}(KH04)\), it is assumed that the He-shell burning is stable and that there is no mass loss.

2. If \(|\dot{M}_{2}|\) is less than \(\dot{M}_{cr}\) but higher than the minimum accretion rate of weak He-shell flashes, \(\dot{M}_{low} = 4.0 \times 10^{-8}M_{\odot}\text{yr}^{-1}\) (Woosley, Taam & Weaver 1986), He-shell flashes occur and a part of the envelope mass is assumed to be blown off from the surface of the WD. The mass growth rate of WDs in this case is linearly interpolated from a grid computed by KH04, where a wide range of WD mass and accretion rate were calculated for the He-shell flashes.

3. If \(|\dot{M}_{2}|\) is lower than \(\dot{M}_{low}\), the He-shell flashes will be so strong that no mass can be accumulated on to the WD.

We define the mass growth rate of the CO WD, \(\dot{M}_{CO}\), as

\[ \dot{M}_{CO} = \eta_{He}|\dot{M}_{2}|, \]

(3)

where \(\eta_{He}\) is the mass accumulation efficiency for He-shell burning. According to the assumptions above, the values of \(\eta_{He}\) are:

\[ \eta_{He} = \begin{cases} \frac{\dot{M}_{cr}}{\dot{M}_{2}}, & |\dot{M}_{2}| > \dot{M}_{cr}, \\ 1, & \dot{M}_{cr} \geq |\dot{M}_{2}| \geq \dot{M}_{st}, \\ \eta_{He}, & \dot{M}_{st} < |\dot{M}_{2}| \geq \dot{M}_{low}, \\ 0, & |\dot{M}_{2}| < \dot{M}_{low}. \end{cases} \]

(4)

We incorporate the prescriptions above into Eggleton’s stellar evolution code and follow the binary evolution of WD + He star systems. The mass lost from these systems is assumed to take away specific orbital angular momentum of the accreting WD. We have calculated the evolution of about 2600 WD + He star systems, and obtained a large, dense model grid. The initial mass of the donor star, \(M_{2}\), ranges from 0.85–3.1M⊙; the initial mass of the CO WD, \(M_{WD}\), ranges from 0.865–1.20M⊙; the initial orbital period of the binary system, \(P_{i}\), changes from the minimum value at which a He zero-age MS (He ZAMS) star would fill its Roche lobe to \(~316\) d, where the He star fills its Roche lobe at the end of the Hertzsprung gap.

3 BINARY EVOLUTION RESULTS

3.1 Typical binary evolution calculations

In Figs 1–4, we present three representative cases of our binary evolution calculations according to the condition of the binary system at the moment of SN explosion, and display one special case for producing SNe Ia. In panels (a) of these figures, we show the \(M_{1}\), \(M_{CO}\) and \(M_{WD}\) with varying time, while panels (b) are the evolutionary tracks of the He stars in the Hertzsprung–Russell diagram, where the evolution of the orbital periods is also shown.

(i) Case I (see Fig. 1). The binary system is in the weak He-shell flash phase at the moment of the SN explosion. The binary shown in this case is \((M_{1}, M_{WD}, \log(P_{i}/\text{day})) = (1.35, 0.9, -1.20)\), where \(M_{1}\), \(M_{WD}\) and \(P_{i}\) are the initial mass of the He star and the CO WD in solar masses, and the initial orbital period
Figure 1. A representative case of binary evolution calculations, in which the binary system is in the weak He-shell flashes phase at the moment of the SN explosion. In panel (a), the solid, dashed and dash–dotted curves show $\dot{M}_2$, $\dot{M}_{\text{CO}}$ and $M_{\text{WD}}$ varying with time, respectively. In panel (b), the evolutionary track of the donor star is shown as a solid curve and the evolution of orbital period is shown as a dash–dotted curve. Dotted vertical lines in both panels and asterisks in panel (b) indicate the position where the WD is expected to explode as a SN Ia. The initial binary parameters and the parameters at the moment of the SN Ia explosion are also given in these two panels.

Figure 2. Similar to Fig. 1, but the binary system is in the stable He-shell burning phase at the moment of the SN explosion.

Figure 3. Similar to Fig. 1, but the binary system is in the optically thick wind phase at the moment of the SN explosion.
in days, respectively. In this case, the He star fills its Roche lobe after the exhaustion of central He (it now contains a CO core), and this results in case BB mass transfer.\(^1\) The mass transfer rate \(\dot{M}_2\) exceeds \(M_\text{tr}\) soon after the onset of RLOF, leading to a wind phase, where a part of the transferred mass is blown off in an optically thick wind, and the mass that is left is accumulated on to the WD. After about \(5 \times 10^4\) yr, \(\dot{M}_2\) drops below \(M_\text{tr}\) but remains higher than \(M_\text{tr}\). Thus, the optically thick wind stops and the He-shell burning is stable. With the continuous decrease of \(\dot{M}_2\), the system enters into a weak He-shell flash phase after about \(5 \times 10^4\) yr. The WD always grows in mass until it explodes as a SN Ia in the weak He-shell flash phase. At the SN explosion moment, the mass of the donor star is \(M_2^{\text{SN}} = 0.8030\ M_\odot\) and the orbital period \(P_{\text{SN}}/\text{day} = -1.1940\).

(ii) Case 2 (see Fig. 2). The binary system is in the stable He-shell burning phase at the moment of the SN explosion. The binary in this case is \((M_2', M_\text{WD}, \log(P/\text{day})) = (1.40, 1.00, -1.10)\). The binary evolves in a similar way to that of Case 1, but it is in a stable He-shell burning stage when the CO WD reaches \(1.378\ M_\odot\). The binary parameters at \(M_\text{WD} = 1.378\ M_\odot\) are \(M_2^{\text{SN}} = 1.0070\ M_\odot\) and \(\log(P_{\text{SN}}/\text{day}) = -1.1296\).

(iii) Case 3 (see Fig. 3). The binary system is in the optically thick wind phase at the moment of the SN explosion. The binary in this case is \((M_2', M_\text{WD}, \log(P/\text{day})) = (1.80, 1.10, -0.60)\). Since the initial mass of the WD is more massive than that of the other two cases above, the WD may grow in mass to the Ch mass more easily, i.e. it is still in the optically thick wind phase when \(M_\text{WD} = 1.378\ M_\odot\), at which point \(M_2^{\text{SN}} = 1.2047\ M_\odot\) and \(\log(P_{\text{SN}}/\text{day}) = -0.6232\).

(iv) Case 4 (see Fig. 4). This case differs from the three above. Before the SN explosion, the binary system experiences two mass transfer phases. The binary in this case is \((M_2', M_\text{WD}, \log(P/\text{day})) = (1.25, 1.10, -1.30)\). Owing to the short initial orbital period of the system, angular momentum loss induced by GWR leads the He star to fill its Roche lobe before the exhaustion of central He, resulting in case BA mass transfer. The mass transfer continues to proceed until the mass donor starts to shrink below its Roche lobe, terminating the mass transfer phase. After it has exhausted the He in its core, the He star expands and fills its Roche lobe again when it evolves to the subgiant stage, leading to case BB evolution. The following evolution of this system is similar to Case 1. When the accreting WD grows to the Ch mass, the binary is in the He-shell flash phase, and the binary parameters are \(M_2^{\text{SN}} = 0.6983\ M_\odot\) and \(\log(P_{\text{SN}}/\text{day}) = -1.1848\).

3.2 Initial parameters for SN Ia progenitors

Figs 5–7 show the final outcomes of about 2600 binary evolution calculations in the initial orbital period–secondary mass \((P_i - M_2')\) plane, where the filled symbols are for those resulting in SN Ia explosions. The different cases described in Section 3.1 are plotted with different symbols, i.e. the filled squares, circles and triangles denote that the WD explodes in the optically thick wind phase, the stable He-shell burning phase and the weak He-shell flash phase, respectively. Some WD + He star systems fail to produce SNe Ia because of He nova explosions (which prevent the WD growing in mass; the crosses in these figures) or dynamically unstable mass transfer (resulting in a common envelope; open circles in these figures). Note that the left boundaries of the initial log \(P_i - M_2'\) plane in these figures are determined by the minimum value of \(\log P_i\) at which the He ZAMS star would fill its Roche lobe.

The contours of initial parameters for producing SNe Ia are also presented in these figures. The left boundaries of the contours in these figures (Figs 5–6 and panel (c) of Fig. 7) are set by the condition that RLOF starts when the secondary is on the He ZAMS,\(^2\) while systems beyond the right boundary experience mass transfer at a very high rate due to the rapid expansion of the He stars in the subgiant stage and lose too much mass via the optically thick wind, preventing the WDs increasing their masses to the Ch mass. The upper boundaries are also set mainly by a high mass transfer rate, owing to a large mass ratio. The lower boundaries are constrained by the requirements that the mass transfer rate \(M_2\) should be high enough to ensure the WD can grow in mass and that the donor

\(^1\) We distinguish case BB (Roche-lobe overflow occurs after He-core burning but before carbon ignition) from case BA (in which mass transfer is initiated during He-core burning) (see Dewi et al. 2002).

\(^2\) Note that the upper parts of the left boundaries are constrained mainly by a high mass transfer rate because of orbit decay induced by GWR and a large mass ratio, which leads to much of the mass being lost from the systems by way of the optically thick wind.
Progenitors of SNe Ia

Figure 5. Final outcomes of the binary evolution calculations in the initial orbital period–secondary mass (log $P_i$, $M_i$) plane of the CO WD + He star system for an initial WD mass of $1.2 M_\odot$. The filled symbols are for those resulting in SN Ia explosions, i.e. the filled squares, circles and triangles denote that the WD explodes in the optically thick wind phase, the stable He-shell burning phase and the weak He-shell flash phase, respectively (see Cases 1–3 in Section 3.1). Crosses indicate systems that may experience He novae, preventing the WD from reaching $1.378 M_\odot$, and open circles are those under dynamically unstable mass transfer.

Figure 6. Similar to Fig. 5, but for an initial WD mass of $1.1 M_\odot$. 
should be sufficiently massive for enough mass to be transferred on to the WD to reach the Ch mass.

There is a time delay (up to about $10^6$ yr) from the formation of most WD + He star systems up to the onset of RLOF, and this time delay varies with the component masses and initial orbital periods. Fig. 8 shows the contours at the onset of RLOF for producing SNe Ia for the primary mass in the log $P_r$ -- $M_r^2$ plane for various WD masses (i.e. $M_{\text{WD}} = 0.865$, 0.9, 1.0, 1.1 and 1.2 $M_\odot$), where $P_r$ and $M_r^2$ are the orbital period and the mass of the He companion star at the onset of RLOF, respectively. Note that the enclosed region almost vanishes for $M_{\text{WD}} = 0.865 M_\odot$, which is then assumed to be the minimum WD mass for producing SNe Ia from this channel. If the parameters of a CO WD + He star system at the onset of RLOF are located in the contours, a SN Ia is then assumed to be produced. Thus, these contours can be expeditiously used in BPS studies.

4 BIRTHRATE OF SNe Ia

Adopting a prescription similar to that of Hachisu et al. (1999b) and based on Fig. 8 of this paper, we can roughly estimate the Galactic SN Ia birthrate from the He star donor channel by using equation (1) of Iben & Tutukov (1984), i.e.

$$v = 0.2 \Delta q \int_{M_A}^{M_B} \frac{dM}{M^{2.5}} \Delta \log A \text{ yr}^{-1},$$

where $\Delta q$, $\Delta \log A$, $M_A$ and $M_B$ are the appropriate ranges of the initial mass ratio, initial separation and lower and upper limits of the primary mass for producing SNe Ia in solar masses, respectively. We give the details of the calculations in the following.

To estimate the birthrate of SNe Ia, we divide the initial WD mass of $M_{\text{WD}}$ into three intervals: $0.9$–$1.0 M_\odot$, $1.0$–$1.1 M_\odot$ and $1.1$–$1.2 M_\odot$ (see also Hachisu et al. 1999b). We ignore the range $M_{\text{WD}} = 0.865$–$0.9 M_\odot$, since its birthrate is too small to contribute to the SN Ia birthrate as seen in Fig. 8. We use equation (11) of Yungelson et al. (1995) to estimate $M_A$ and $M_B$, i.e. the final core mass (CO WD mass) versus the ZAMS mass relation:

$$\log M_{WD} = -0.22 + 0.36 \left( \log \frac{M_i}{M_\odot} \right)^{2.5},$$

where $M_{WD}$ and $M_i$ are the mass of the final CO WD and the ZAMS in solar masses, respectively. In addition, similarly to Hachisu et al. (1999b), we also use an approximation relation to obtain $\Delta \log A$:

$$\Delta \log A \approx \frac{2}{3} \Delta \log P^r,$$

where $\Delta \log P^r$ is taken from the SN Ia region in Fig. 8 and the factor of $2/3$ comes from the conversion between the period and the separation. Taking a WD mass interval of $1.1$–$1.2 M_\odot$ as

Note that the contours for SNe Ia between Figs 5–7 and Fig. 8 have some differences, i.e. Figs 5–7 are for the initial parameters while Fig. 8 is for those at the onset of RLOF. GWR may change the orbital period during this time, especially for binaries with short orbital periods (i.e. less than 1 d in this paper). For example, the left boundary of the contour for $M_{\text{WD}} = 1.2 M_\odot$ in Fig. 8 has shorter periods than that in Figs 5–7, because angular momentum loss via GWR is greater in short-period binary systems than in long-period systems.

The data points of these contours and the interpolation FORTRAN code for these contours may be obtained from wangbo@ynao.ac.cn.
Table 1. The birthrates of SNe Ia for different WD mass intervals.

| $M'_\text{WD}$ (M$_\odot$) | $\Delta \log A$ | $M_A$ (M$_\odot$) | $M_B$ (M$_\odot$) | $\Delta q$ | $\nu_{\text{WD}}$ (10$^{-3}$ yr$^{-1}$) |
|---------------------|----------------|-----------------|-----------------|-----------|-----------------|
| 0.9–1.0             | 1.0 ± 2/3      | 5.60            | 6.63            | 0.02      | 0.03            |
| 1.0–1.1             | 1.8 ± 2/3      | 6.63            | 7.58            | 0.18      | 0.31            |
| 1.1–1.2             | 3.7 ± 2/3      | 7.58            | 8.48            | 0.34      | 0.82            |

an example, we find that SN Ia explosions occur for the ranges $M_{i1} = 7.58–8.48$ M$_\odot$, $M_{i10} = 0.95–3.0$ M$_\odot$ and $\Delta \log A = 3.7 \times 2/3$, where $M_{i1}$ is the initial mass of the primary at the ZAMS and $M_{i10}$ is the initial mass of the He star. Using Eggleton’s stellar evolution code, we can obtain an initial ZAMS mass $M_i = 5.60$ M$_\odot$ for a final He-core mass of 0.95 M$_\odot$ (i.e. He star mass).

Assuming the initial mass of the secondary at the ZAMS is not more than that of the primary at the ZAMS, we constrain the range of $M_{i1}$ to be from 5.60 M$_\odot$–1.1 M$_\odot$, where $M_{i1}$ is the initial mass of the secondary at the ZAMS. Thus, we obtain $\nu_{\text{WD},1.1–1.2} \simeq 0.82 \times 10^{-3}$ yr$^{-1}$ by substituting $\Delta \log A = 3.7 \times 2/3$, $\Delta q = 1 - (5.60/8.48) = 0.34$, $M_A = 7.58$ and $M_B = 8.48$ into equation (5). The SN Ia birthrates for different WD mass intervals are summarized in Table 1. Note that for different initial WD masses the birthrate tendency of this channel is different from that of the WD + MS channel, i.e. massive WDs for producing SNe Ia have a high birthrate for the WD + He star channel. This is because massive WDs often have massive He stars as their companions.

Finally, the sum of SN Ia birthrates for the three intervals (0.9–
1.0 M$_\odot$, 1.0–1.1 M$_\odot$ and 1.1–1.2 M$_\odot$) gives $\nu \sim 1.2 \times 10^{-3}$ yr$^{-1}$ in the Galaxy, which is lower than the value inferred observationally (i.e. $3.4 \times 10^{-3}$ yr$^{-1}$; van den Bergh & Tammann 1991; Cappellaro & Turatto 1997).

5 DISCUSSION

In our work, we have not considered the influence of rotation on the He-accreting WDs. The calculations of Yoon, Langer & Scheithauer (2004) showed that if rotation is taken into account He burning is much less violent than for WDs without rotation. This may significantly increase the accretion efficiency ($\eta_{\text{ac}}$ in this paper). Meanwhile, the maximum stable mass of a rotating WD may be above the standard Ch mass (i.e. the super-Ch mass model: Uenishi, Nomoto & Hachisu 2003; Yoon & Langer 2005). However, in this paper we mainly focus on the Ch-mass explosions of the accreting WDs.

Yoon & Langer (2003, hereafter YL03) only considered the case BB evolution of a CO WD + He star system that could produce a SN Ia. In this paper, we systematically studied the He star donor channel for the progenitors of SNe Ia (including both case BA and case BB binary evolution) and showed the contours of SNe Ia for various initial WD masses. The binary studied in YL03 is located within the contours of this paper. However, there are some differences between our assumptions and theirs as regards mass accumulation efficiency. This is mainly because the effect of wind mass loss in YL03’s calculation is taken into account based on an empirical formula for Wolf–Rayet star mass loss, while we used an optically thick wind model (Kato & Hachisu 1994; Hachisu et al. 1996) and adopted the prescription of KH04 for the mass accumulation efficiency of the He-shell flashes on to the WDs.

The estimated birthrate of this channel is $\nu = 1.2 \times 10^{-3}$ yr$^{-1}$, which is comparable to that of the WD + MS channel (this is considered an important channel for SNe Ia: Han & Podsiadlowski 2004). Thus, the He star donor channel should not be ignored when we study the progenitors of SNe Ia, and this channel may in theory increase the contribution of the SD Ch scenario to the SN Ia birthrate. Note that the estimated birthrate may be higher than that in reality, since the long-orbital-period (i.e. $\geq 1$ day in Fig. 8) systems considered to produce SNe Ia in equation (1) of Iben & Tutukov (1984) may not actually contribute to SNe Ia. Moreover, Umeda et al. (1999) concluded that the upper limit mass for CO cores born in binaries is about 1.07 M$_\odot$. If this value is adopted as the upper limit of the CO WD, the birthrate of SNe Ia from this channel will decrease to be $\sim 0.2 \times 10^{-3}$ yr$^{-1}$ in the Galaxy.

Some precursory studies (Iben & Tutukov 1994; YL03) suggested that WD + He star systems may appear as supersoft X-ray sources (SSSs) before SN Ia explosions. The initial orbital periods of WD + He star systems producing SNe Ia for this channel range from $\sim 1$ h to $\sim 200$ d, which may explain SSSs with various orbital periods. We can estimate the X-ray luminosity of a WD + He star system by $L_x \sim \epsilon_{\text{He}}/M_2$, where $\epsilon_{\text{He}} = 6 \times 10^{37}$ erg g$^{-1}$ is the energy generation rate owing to He burning. A WD + He star system has a luminosity around $10^{37}$–$10^{38}$ erg s$^{-1}$ when He burning is stable on the surface of the WD, consistent with that of observed SSSs ($L_x = 10^{36}$–$10^{38}$ erg s$^{-1}$; Kahabka & van den Heuvel 1997). Note that strong He lines are prominent in the luminous SSSs (see Kahabka & van den Heuvel 1997). Thus, we emphasize that SN Ia progenitors in the He star donor channel may appear as SSSs during the stable He-shell burning phase without winds.4 By multiplying the birthrate, $\sim 1.2 \times 10^{-3}$ yr$^{-1}$, by the average duration of the SSS phase, $\sim$ several times 10$^5$ yr, we estimate that the current number of this type of progenitor existing as SSSs in the Galaxy should be from a few to several hundred. However, we do not observe such a number of WD + He star systems in the SSS phase. This may be attributed to the Galactic interstellar absorption of SSSs (Di Stefano & Rappaport 1994; Hachisu, Kato & Nomoto 2008). Moreover, Di Stefano & Rappaport (1994) also suggested that circumstellar matter may play a role in the obscuration of X-rays (see also Hachisu et al. 2008).

Generally, a CO WD + He star system is produced from an intermediate-mass binary, which can be found in stellar populations with relatively recent star formation. The minimum He star mass for producing SNe Ia from this channel is 0.95 M$_\odot$, with which we can roughly estimate the maximum delay time of this channel. The initial ZAMS mass $M_i = 5.60$ M$_\odot$ can produce a He star mass of 0.95 M$_\odot$ (see Section 4). The MS lifetime is about 81 Myr for a star of 5.6 M$_\odot$ (Eggleton 2006). Moreover, we should consider the MS lifetime of He stars, since the He stars in long-orbital-period systems experience RLOF after the exhaustion of their central He. The MS lifetime of a 0.95 M$_\odot$ He star is about 18 Myr. Thus, the maximum delay time of this channel is about 10$^5$ yr, i.e. the He star donor channel can explain SNe Ia with short delay times ($\lesssim 10^3$ yr; Mannucci et al. 2006; Aubourg et al. 2008). Note that Hachisu et al. (2008) investigated new evolutionary models for SN Ia progenitors, introducing the mass-stripping effect on a MS or slightly evolved companion star by winds from a mass-accreting WD. The model can also explain the presence of very young ($\lesssim 10^5$ yr) populations of SN Ia progenitors (see also Hachisu, Kato & Nomoto 2008).

When WD + He star systems explode as SNe Ia, the SN Ia spectra may sometimes show signs of He. Unfortunately, the He associated with SNe Ia has not been detected in past years (Marion et al. 2003; Mattiä et al. 2005). Therefore, Kato et al. (2008) suggested that...

4 Massive wind may absorb soft X-rays, which cannot then be detectable (Hachisu et al. 1999b; Kato & Hachisu 2003).
SNe Ia from this channel may be rare. However, further study of this channel is necessary, since it can explain some SNe Ia with short delay times. In addition, GWR is strong in WD + He star systems with short orbital periods. Thus, the WD + He star systems with short orbital periods may possibly be detectable sources of GWR.

6 SUMMARY

Using an optically thick wind model (Kato & Hachisu 1994; Hachisu et al. 1996) and adopting the prescription of KH04 for the mass accumulation efficiency of the He-shell flashes on to the WDs, we systematically studied the He star donor channel for producing SN Ia progenitors and revealed the parameter space for SNe Ia from this channel. Our study shows that this channel is noteworthy for producing SNe Ia, i.e. the birthrate of SNe Ia is \( \sim 1.2 \times 10^{-3} \) yr\(^{-1}\) in the Galaxy. In addition, the minimum mass of a CO WD for producing SNe Ia from this channel may be as low as 0.865 M\(_{\odot}\). According to the orbital period range and X-ray luminosities of WD + He star systems, we consider that WD + He star systems may appear as SSSs before SN Ia explosions, which is consistent with YL03. Importantly, the He star donor channel can explain SNe Ia with short delay times (\( \lesssim 10^3 \) yr). Also, WD + He star systems with short orbital periods may be detectable sources of GWR, and the contours of the log \( P^3 - M^{1/3} \) plane at the beginning of RLOF can be used in BPS studies. In future investigations, we will study the properties of companions at the moment of the SN explosion, which could perhaps be verified by future observations.

ACKNOWLEDGMENTS

We thank an anonymous referee for valuable comments that helped to improve the paper. BW thanks Professor M. Kato of Keio University for helpful discussions, and Professor Ph. Podsiadlowski of Oxford University for helpful discussions during a visit to NAOC/YNAO in April 2008. This work is supported by the National Natural Science Foundation of China (Grant Nos. 10433030, 10521001, 2007CB815406 and 10603013) and the Foundation of the Chinese Academy of Sciences (Grant No. 06YQ011001).

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