Companion stars of Type Ia supernovae and single low-mass white dwarfs

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ABSTRACT
Recent investigations of the white dwarf (WD) + main-sequence (MS) channel of Type Ia supernovae (SNe Ia) imply that this channel may be the main contribution to the old population ($\gtrsim 1$ Gyr) of SNe Ia. In the WD + MS channel, the WD could accrete material from a main-sequence or a slightly evolved star until it reaches the Chandrasekhar mass limit. The companions in this channel would survive after SN explosion and show distinguishing properties. In this Letter, based on SN Ia production regions of the WD + MS channel and three formation channels of WD + MS systems, we performed a detailed binary population synthesis study to obtain the properties of the surviving companions. The properties can be verified by future observations. We find that the surviving companions of the old SNe Ia have a low mass, which provides a possible way to explain the formation of the population of single low-mass WDs ($< 0.45 \, M_\odot$).

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

1 INTRODUCTION
Type Ia supernovae (SNe Ia) appear to be good cosmological distance indicators owing to their high luminosities and remarkable uniformity, and have been applied successfully in determining cosmological parameters (e.g. $\Omega$ and $\Lambda$; Riess et al. 1998; Perlmutter et al. 1999). However, several key issues related to the nature of their progenitors and the physics of the explosion mechanisms are still not well understood (Hillebrand & Niemeyer 2000; Wang et al. 2008; Podsiadlowski 2010), and no SN Ia progenitor system before the explosion has been conclusively identified. These uncertainties may raise doubts about the distance calibration which is purely empirical and based on the SN Ia sample of the low-redshift Universe ($z < 0.05$; Phillips 1993).

It is widely accepted that SNe Ia are thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) in binaries (for the review see Nomoto, Iwamoto & Kishimoto 1997). Over the past few decades, two families of SN Ia progenitor models have been proposed, i.e. the double-degenerate (DD) and single-degenerate (SD) models. In the DD model, two CO WDs with a total mass larger than the Chandrasekhar mass limit may coalesce and then explode as an SN Ia (Iben & Tutukov 1984; Webbink 1984; Han 1998). Although it is suggested that the DD model likely leads to an accretion-induced collapse rather than to an SN Ia (Nomoto & Iben 1985), it is still too early to exclude the model as it may contribute to a few SNe Ia (Howell et al. 2006; Pakmor et al. 2010). In the SD model, the companion is probably a main-sequence (MS) or a slightly evolved star (WD + MS channel), or a red giant (RG) star (WD + RG channel; e.g. Whelan & Iben 1973; Hachisu, Kato & Nomoto 1996; Li & van den Heuvel 1997; Yungelson & Livio 1998; Langer et al. 2000; Han & Podsiadlowski 2004, 2006; Chen & Li 2007; Lü et al. 2009; Meng & Yang 2010a; Wang & Han 2010a; Wang, Li & Han 2010a, hereafter WLH10). Meanwhile, a CO WD may also accrete material from a He star to increase its mass to the Chandrasekhar mass limit (WD + He star channel; Solheim & Yungelson 2005; Ruiter, Belczynski & Fryer 2009; Wang et al. 2009a,b; Wang & Han 2010b). An explosion following the merger of two WDs would leave no remnant, while the companion in the SD model would survive and potentially be identifiable. A surviving companion in the SD model would evolve to a WD finally, and Hansen (2003) suggested that the SD model could potentially explain the properties of halo WDs, e.g. their space density and ages. Note that there has been no conclusive proof yet that any individual object is the surviving companion of an SN Ia. It would be a promising method to test SN Ia progenitor models by identifying their surviving companions.

By considering the effect of the thermal–viscous instability of accretion disc on the evolution of WD binaries, WLH10 recently enlarged the regions of the WD + MS channel for producing SNe Ia. According to a detailed binary population synthesis (BPS) approach, WLH10 found that this channel is effective for producing SNe Ia ($\sim 1.8 \times 10^{-3} \, \text{yr}^{-1}$ in the Galaxy). This study also implied that the WD + MS channel may be the main contribution to the old population ($\gtrsim 1$ Gyr) of SNe Ia. The companions in this channel would survive and show distinguishing properties.
At present, the existence of a population of single low-mass ($<0.45 \, M_\odot$) WDs (LMWDs) is supported by some observations (e.g. Kilic, Stanek & Pinsonneault 2007b). (1) The first two LMWDs have been implied by the work of Marsh, Dhillion & Duck (1995). They carried out radial velocity measurements of seven LMWDs, and found that two of the WDs, WD 1353+409 and WD 1614+136 do not show any radial velocity variations. (2) Maxted, Marsh & Moran (2000) also presented 14 LMWDs with no detectable radial velocity variations from a larger radial velocity survey of 71 WDs. (3) A recent analysis of 348 H atmosphere WDs from the Palomar–Green (PG) survey has revealed 30 LMWDs (Liebert, Bergeron & Holberg 2005). Kilic et al. (2007b) concluded that 47 per cent of the PG LMWDs searched for companions seem to be single. (4) The ESO SN Ia Progenitor Survey (SPY) searched for radial velocity variations in more than a thousand WDs using the Very Large Telescope (Napiwotzki et al. 2001). Kilic et al. (2007b) also concluded that 15 of 26 LMWDs discovered in the SPY project do not show any radial velocity variations, corresponding to a single LMWD fraction of 58 per cent (see also Napiwotzki et al. 2007).

The formation of the single LMWDs is still unclear. It is suggested that the single LMWDs could be produced by single old metal-rich stars which experience significant mass loss prior to the He flash (Kalirai et al. 2007; Kilic et al. 2007b). However, within the age of the Universe, it is almost certainly impossible for the single stars to produce WDs with mass close to 0.3 $M_\odot$, or even some extremely LMWDs with mass as low as 0.2 $M_\odot$ (e.g. Kilic et al. 2007a,b; Justham et al. 2009). Furthermore, the study of initial–final mass relation for stars by Han, Podsiadlowski & Eggleton (1994) implied that only LMWDs with masses $>0.4 \, M_\odot$ might be produced from such a single-star channel, even at high metallicity (Meng, Chen & Han 2008). Thus, it would be difficult to conclude that single stars can produce LMWDs. Justham et al. (2009) recently inferred an attractive formation channel for the single LMWDs, which could have been formed in binaries where their companions have exploded as SNe Ia. Note that Nellen & Tauris (1998) also proposed an alternative scenario to form single LMWDs from a solar-like star accompanied by a massive planet, or a brown dwarf, in a relatively close orbit.

Han (2008) obtained many properties of the surviving companions of the SNe Ia with intermediate delay times ($100 \, \text{Myr} \sim 1 \, \text{Gyr}$; the delay times of SNe Ia are defined as the time intervals between the star formation and SN Ia explosion). Wang & Han (2009) studied the properties of the companions of the SNe Ia with short delay times ($<100 \, \text{Myr}$) from the WD + He star channel. The properties can be verified by future observations (e.g. the masses, the spatial velocities, the effective temperatures, the luminosities, the surface gravities, etc; referring to Wang & Han 2009). The purpose of this Letter is to investigate the properties of the surviving companions of the old SNe Ia from the WD + MS channel inferred in WLH10, and to explore whether the surviving companions, later in their evolution, could explain the existing population of single LMWDs. In Section 2, we describe the BPS method for obtaining the properties of the companions. The BPS results and discussion are given in Section 3.

## 2 Binary Population Synthesis

In the WD + MS channel, the progenitor of an SN Ia is either a close WD + MS or WD + subgiant system, which has most likely emerged from the common envelope (CE) evolution of a binary involving a giant star. The CE ejection is still an open problem. Similar to the work of Wang et al. (2009b), we also use the standard energy equations (Webbink 1984) to calculate the output of the CE phase. For this prescription of the CE ejection, there are two highly uncertain parameters, i.e. $\alpha_{ce}$ and $\lambda$, where $\alpha_{ce}$ is the CE ejection efficiency, and $\lambda$ is a structure parameter that depends on the evolutionary stage of the donor. As in previous studies, we combine $\alpha_{ce}$ and $\lambda$ into one free parameter $\alpha_{ce}$, and set it to be 0.5 (for details see Wang et al. 2009b).

To obtain the distributions of properties of the surviving companions, we performed a Monte Carlo simulation in the BPS study. In the simulation, by using the Hurley’s rapid binary evolution code (Hurley, Pols & Tout 2000; Hurley, Tout & Pols 2002), we followed the evolution of $1 \times 10^3$ sample binaries from the star formation to the formation of the WD + MS systems according to three evolutionary channels (i.e. the He star channel, the EAGB channel and the TPAGB channel; the three channels here all refer to the WD progenitor’s evolutionary phase when it encounters a Roche lobe overflow (RLOF) event, for details see WLH10). If a binary evolves to a WD + MS system, and if the system, at the onset of the RLOF phase, is located in the SN Ia production regions (see fig. 6a of WLH10) in the plane of (log $P$, $M_i$) for its $M_{WD}$, where $P$, $M_i$ and $M_{WD}$ are, respectively, the orbital period, the secondary’s mass and the WD’s mass of the WD + MS system at the onset of the RLOF, we assume that an SN Ia is resulted, and the properties of the WD + MS system at the moment of SN explosion are obtained by interpolation in the three-dimensional grid ($M_{WD}$, $M_i$, log $P$) of the $\sim 2400$ close WD + MS systems calculated in WLH10.

In the BPS study, the primordial binary samples are generated in the Monte Carlo way. We adopted the following input for the simulation (e.g. Wang et al. 2009b, 2010b).

(1) The initial mass function (IMF) of Miller & Scalo (1979) is adopted.

(2) We take a constant mass-ratio ($q'$) distribution (Goldberg & Mazeh 1994):

$$n(q') = \begin{cases} 1, & 0 < q' \leq 1, \\ \frac{1}{q'^{2}}, & q' > 1. \end{cases}$$

(3) We assume that all stars are members of binaries and that the distribution of separations is constant in log $a$ for wide binaries, where $a$ is separation and falls off smoothly at a small separation

$$n(a) = \begin{cases} \alpha_{ap}(a/a_0)^{p}, & a \leq a_0, \\ \alpha_{ap}, & a_0 < a < a_1, \end{cases}$$

where $\alpha_{ap} \approx 0.07$, $a_0 = 10 \, R_\odot$, $a_1 = 5.75 \times 10^6 \, R_\odot = 0.13 \, \text{pc}$ and $p \approx 1.2$. This distribution implies that the numbers of wide binaries per logarithmic interval are equal, and that about 50 per cent of stellar systems have orbital periods less than 100 yr (Han, Podsiadlowski & Eggleton 1995).

(4) A circular orbit is assumed for all binaries. The orbits of semidetached binaries are generally circularized by tidal forces on a time-scale which is much smaller than the nuclear time-scale.

(5) The star formation rate (SFR) is taken to be constant over the past 15 Gyr.

## 3 Results and Discussion

The simulation gives current-epoch distributions of many properties of companions at the moment of SN explosion, e.g. the masses, the orbital periods, the orbital separations, the orbital velocities, the effective temperatures, the luminosities, the surface gravities, the surface abundances, the mass-transfer rates, the mass-loss rates of the optically thick stellar winds, etc. The simulation also shows...
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Figure 1. Distribution of properties of the companions in the plane of $(V_{\text{orb}}, M_{\text{SN}}^2)$ at the current epoch, where $V_{\text{orb}}$ is the orbital velocity and $M_{\text{SN}}^2$ the mass at the moment of SN explosion.

The distributions correspond to the moment of SN explosion. The physical quantities depicted in the figure were calculated based on the assumption that the companion (e.g. at the time when the WD explodes) has not yet been affected by the explosion itself. Since SN explosion is expected to have a direct impact upon the surviving companion, one would expect that the distributions would look somewhat modified at a later time. For example, the SN ejecta will interact with its companion. The companions will be stripped of some mass (see the next paragraph) and receive a kick velocity that is perpendicular to the orbital velocity. Marietta, Burrows & Fryxell (2000) presented several high-resolution two-dimensional numerical simulations of the impact of SN Ia explosion with companions. The study implied that this impact makes the companion in the WD + MS channel receive a kick of 49–86 km s$^{-1}$. With detailed stellar models and realistic separations that were obtained from binary evolution, Meng, Chen & Han (2007) obtained a similar kick velocity 30–90 km s$^{-1}$. Thus, a surviving companion has a space velocity larger by $\sim$10 per cent than that in Fig. 1.

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We find that the distribution of the mass for the companions is bimodal (see Fig. 2). The left-hand peak results from the companions of SNe Ia with long delay times, while the right from the companions of SNe Ia with intermediate delay times. For SNe Ia with intermediate delay times, SNe Ia explosions occur when the companion is a MS or a slightly evolved star. The study of Marietta et al. (2000) implied that the impact of the SN explosion makes the MS or the slightly evolved companion lose a mass of 0.15–0.17 $M_\odot$.

The initial parameters of the primordial binaries and the WD + MS systems that lead to SNe Ia. Figs 1–5 are selected distributions that may be helpful for identifying the surviving companions.

Fig. 1 shows the distributions of the masses and the orbital velocities of companions at the moment of SN explosion. In the figure, the companion has an orbital velocity of $\sim$80–220 km s$^{-1}$ for a corresponding mass of $\sim$0.2–1.8 $M_\odot$ at the moment of SN explosion.

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while Meng et al. (2007) obtained a lower ‘stripped mass’ ∼0.03–0.13 M⊙. A surviving companion of SNe Ia with intermediate delay times therefore has a mass lower by ∼0.1 M⊙. However, for the SNe Ia with long delay times, SN Ia explosions occur when the companion evolves to the RG stage. Marietta et al. (2000) found that an RG donor will lose almost its entire envelope (96–98 per cent) owing to the impact of the SN explosion and leave only the core of the star. Thus, the surviving companions of SNe Ia with long delay times will contribute to the population of single LMWDs.

WLH10 inferred that the WD + RG channel of SNe Ia, in which the WD begins to accrete material from an RG star, has a long delay time from the star formation to SN explosion due to the low initial mass (≤1.5 M⊙) of the RG donors. So, all SNe Ia from this channel also contribute to the old populations of SNe Ia, and the companions have a low mass at the moment of SN explosion (see fig. 2 of Wang & Han 2010a), which also provides a possible pathway for the formation of the single LMWDs. However, the Galactic SN Ia birth rate from the WD + RG channel is low (∼3 × 10⁻⁵ yr⁻¹; WLH10) compared with observations, so in this study we mainly focus on the investigation of surviving companions from the WD + MS channel, which may be the main contribution to the population of single LMWDs (note that the theoretical birth rate from the WD + RG channel still contains many potential uncertainties). Here, we emphasize that the surviving companions of the old SNe Ia from the WD + MS and WD + RG channels provide a possible way for the formation of the population of the single LMWDs. We also suggest that the observed single LMWDs may provide evidence that at least some SNe Ia explosions have occurred with non-degenerate donors (such as MS or RG donors).

The time-scale from SN explosion to the formation of a WD from the surviving companion is important in future observational tests, which is related to the evolutionary phase of the surviving companion. If the companion is in the MS stage at the moment of SN explosion, the time-scale mainly depends on the nuclear burning lifetime of the star. We did a test for the evolution of a typical MS surviving companion, which has the mass of 1.04 M⊙ and with central H abundance 0.26 (its remaining MS lifetime is about 840 Myr, and its post-MS lifetime is about 1300 Myr). Thus, on average the nuclear burning lifetime of the MS surviving companion is about 2 Gyr. If the companion is in the RG stage at the moment of SN explosion, the time-scale is mainly decided by the lifetime of the H-shell burning. We also did a test for this case (e.g. a 0.42 M⊙ RG companion star with 0.17 M⊙ He core, the lifetime of the H-shell burning is about 180 Myr. Here, we ignore the thermal equilibrium time-scale from a He core to a WD, since it is short ∼10⁹ yr compared with the time-scale of the H-shell burning). Therefore, a low-mass companion in the RG stage will evolve to a WD more quickly than the massive companion in the MS stage.

Fig. 3 represents the distributions of the effective temperatures and the surface gravities of the companions at the moment of SN explosion. Tycho G was taken as the surviving companion of Tycho’s SN by Ruiz-Lapuente et al. (2004). It has a space velocity of 136 km s⁻¹, more than three times the mean velocity of the companions at the moment of SN explosion. Tycho G was taken as the surviving companion of SN Ia. Ihara et al. (2007) recently also argued that Tycho G may not be the companion of Tycho’s SN, as the star did not show any special properties in its spectrum. The surviving companions of SNe Ia would expect to be contaminated by SN ejecta and show some special characteristics (e.g. Marietta et al. 2000). Thus, whether Tycho G is the surviving companion of Tycho’s SN is still quite debatable.

Fig. 4 shows the distributions of orbital periods and secondary masses of the WD + MS systems at the moment of SN explosion. The orbital periods and secondary masses at this moment are basic input parameters when one simulates the interaction between SN ejecta and its companion. This figure may also help us to verify whether some WD + MS systems observed could explode as SNe Ia. A recurrent nova (U Sco) is indicated by a filled asterisk in the figure, in which the WD mass is about 1.37 M⊙ and its companion is a 1.5 M⊙ MS star (Hachisu et al. 2000). The orbital period of the binary is 1.23 d (SchaefER & KingwALD 1995). Hachisu et al. (2000) concluded that the WD could increase its mass until an SN Ia explosion. If the WD explodes as an SN Ia eventually, the companion would have a slightly smaller mass. The binary orbital period will first decrease and then increase if the mass-ratio reverses. Then, its final position in the figure will move to a lower mass than its present one, and may enter into the most probable area for producing SNe Ia. Thus, U Sco is likely to explode as an SN Ia (see also Meng & Yang 2010b).

If we assume that the companions corotate with their orbits, we can obtain the distributions of their equatorial rotational velocities (see Fig. 5). We see that the surviving companions are fast rotators, so their spectral lines should be broadened noticeably. The rotational velocity of companions from the WD + MS channel is in the range of ∼10–40 km s⁻¹, which is lower than that from the WD + He star channel (∼120–380 km s⁻¹; Wang & Han 2009). This is because the WD + He star channel has shorter orbit periods than that of the WD + MS channel at the moment of SN explosion.

The simulation in this Letter was made with αceλ = 0.5. If we adopt a higher value for αceλ (e.g. 1.5), the birth rate of SNe Ia will be lower than the case of αceλ = 0.5 (the binaries emerged from the CE ejections tend to have slightly closer orbits for αceλ = 0.5 and are more likely to be located in the SN Ia production region). In addition, a high value of αceλ leads to a systematically later explosion time, i.e. the delay time from the star formation to SN explosion will be longer. This is because a high value of αceλ leads to wider WD + MS systems, and, as a consequence, it takes a longer time for the companion to evolve to fill its Roche lobe. For a high value of αceλ (e.g. 1.5), the minimum delay time is ∼360 Myr, while the value is ∼280 Myr for αceλ = 0.5.

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