Companion Stars of Type Ia supernovae with different metallicities

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ABSTRACT

Single degenerate model is the widely accepted progenitor model of Type Ia supernovae (SNe Ia), where a CO WD accretes hydrogen-rich material from its companion to increase its mass. The companion may be a main-sequence star or a subgiant star (WD + MS). When the CO WD approaches the Chandrasekhar mass limit, it explodes as a SN Ia and a part of supernova ejecta collides into the companion envelope. After the impact of the ejecta, the companion survives and may show some special properties. A good way to verify the single degenerate model is to study the interaction between supernova ejecta and its companion, and/or search companion in the remnant of a SN Ia.

Meng, Chen & Han (2009) comprehensively and systemically studied the WD + MS system by detailed binary evolution calculations. Following their studies, we have carried out a series of binary population synthesis studies about the properties of the companions of SNe Ia for different metallicities $Z$. We present the distributions of the masses, $M_{SN}^2$, the radii, $R_{SN}^2$, of companions, and the periods, $P_{SN}$, and the ratios of separations to radii, $A/R_{SN}^2$, of WD + MS systems for various $Z$ at the moment of supernova explosion. These parameters can be applied to constrain the numerical simulation of the interaction between supernova ejecta and its companion. We also show the distributions of some integral properties of companions, i.e. the mass, the space velocity and the surface gravity, for various $Z$ after the interaction. The distributions may help to search companion in a supernova remnant. All the parameters above significantly change with $Z$.

Incorporating the simulation results of interaction between supernovae ejecta and companions in Marietta et al. (2000) and Kasen et al. (2004) into our binary population synthesis study, we found that more than 75% of all supernovae have enough polarization signal which can be detected by spectropolarimetric observations. We also found that 13 to 14 per cent SNe Ia belong to the supernova like 1991T, which is consistent with observations within errors. This may indicate that SNe 1991T-like have not any special properties in physics except for the viewing angle of an observer.

Key words: binaries: close-stars: evolution-supernovae: general-white dwarf: metallicity

1 INTRODUCTION

Type Ia supernovae (SNe Ia) play an important role in astrophysics, especially in cosmology. They appear to be good cosmological distance indicators and are successfully applied to determine cosmological parameters (e.g. $\Omega$ and $\Lambda$). There is a linear relation between the absolute magnitude of SNe Ia and the magnitude difference from maximum to 15 days after B maximum light. The relation is known as Phillips relation (Phillips 1993) and adopted when SNe Ia were taken as the distance indicators. In this case, Phillips relation is assumed to be valid at high redshift, although it was obtained from a low-redshift sample. This assumption is precarious since the exact nature about SNe Ia is still unclear (see the reviews by Hillebrandt & Niemeyer 2000; Leibundgut 2000). If the properties of SNe Ia evolve with redshift, the results for cosmology might be different. Since metallicity may represents redshift to some extent, it is a good method to study the...
properties of SN Ia at various redshift by finding the correlation between the properties and metallicity.

It is widely believed that SN Ia is from the thermonuclear runaway of a carbon-oxygen white dwarf (CO WD) in a binary system. The CO WD accretes material from its companion to increase its mass. When its mass reaches its maximum stable mass, it explodes as a thermonuclear runaway and almost half of the WD mass is converted into radioactive nickel-56 (Branch 2004). The mass of nickel-56 determines the maximum luminosity of SN Ia. The higher the mass of nickel-56 is, the higher the maximum luminosity is (Arnett 1982). Some numerical and synthetic results have shown that metallicity may affect the final amount of nickel-56, and thus the maximum luminosity (Timmes et al. 2003; Travaglio et al. 2003; Podsiadlowski et al. 2006). There is also much evidence about the correlation between the properties of SNe Ia and metallicity in observations (we list here some of the papers on this study, Branch & Bergh 1993; Hamuy et al. 1996; Wang et al. 1997; Cappellaro et al. 1995; Shanks et al. 2002).

Among all the suggested progenitor models of SNe Ia, the single-degenerate Chandrasekhar model (Whelan & Iben 1973; Nomoto, Thielemann & Yokoi 1984) is the most widely accepted progenitor model at present. In the model, a CO WD accretes hydrogen-rich material from its companions until its mass reaches a mass $\sim 1.378 M_\odot$ (close to Chandrasekhar mass, Nomoto, Thielemann & Yokoi 1984), and then explodes as a SN Ia. The companion may be a main sequence star or a subgiant star (WD+MS) or a red-giant star (WD+RG) (Yungelson et al. 1995; Li & van den Heuvel 1997; Hachisu et al. 1999a,b; Nomoto et al. 1999, 2003; Langer et al. 2000; Han & Podsiadlowski 2004; Chen & Li 2004; Han et al. 2005; Wang et al. 2009a,b). In this paper, we focus on the WD + MS channel since it is the most widely accepted channel for SNe Ia (Han & Podsiadlowski 2004; Meng, Chen & Han 2009). Much observational evidence shows the importance of the channel. For example, some WD + MS systems are suggested as the progenitor of SNe Ia (Parthasarathy et al. 2007). Hachisu & Kato (2003a,b) suggested that supersoft X-ray sources (SSSs) may be good candidates for the progenitors of SNe Ia, and some of SSSs belong to WD+MS system. The discovery of the potential companion of Tycho’s supernova seemed to verify the reliability of the WD + MS model (named Tycho G by Ruiz-Lapuente et al. 2004). Recently, Hernández et al. (2009) stressed further the companion nature of Tycho G by analysing the chemical abundances of Tycho G. However, Fuhrmann (2003) argued that the first discovered “companion” might be a Milky Way thick-disk star which is coincidentally passing the vicinity of the remnant of Tycho’s supernova. Ibara et al. (2007) also argued that Tycho G may not be the companion of Tycho’s supernova since the star did not show any special properties in its spectrum, which should be contaminated by supernova ejecta and show some special characters (Marietta et al. 2000; Branch 2004). So, more evidence to confirmed the companion nature of Tycho G is needed.

The knowledge about the companions of SNe Ia after explosions is still unclear. Generally, the supernova ejecta in the single degenerate model collides into the envelope of its companion and strips some hydrogen-rich material from the surface of the companion. After the collision, the companion gains a kick velocity, which is much smaller than orbital velocity, and leaves explosion center at a velocity similar to its orbital velocity (Chen 1974; Wheeler et al. 1974; Fryxell & Arnett 1983; Taam & Fryxell 1984; Chugai 1984; Livne, Tuchman & Wheller 1992; Langer et al. 2000). Marietta et al. (2000) ran several high-resolution two-dimensional numerical simulations of the collision between the ejecta and the companion, where the companion is a MS star, a subgiant (SG) star or a red giant (RG) star. They found that about $0.15 M_\odot - 0.17 M_\odot$ of hydrogen-rich materials are stripped from the surface of a MS or a SG companion and n sense of the collision, there is no difference whatever the companion is a MS star or a SG star. The amount of the stripped material from red-giant companions is even more than $0.5 M_\odot$, i.e. more than 96% of their envelopes is lost. Meng, Chen & Han (2007) used a simple analytic method but a more physical companion model to simulate the interaction and found that the minimum value of the stripped material from a MS companion is diminished from $0.15 M_\odot$ to $0.035 M_\odot$. They suggested that the structure of the companion at the explosion moment may be an important factor to determine the mass of the stripped material. The structure of the companion in Meng, Chen & Han (2007) is obviously different from that of a solar model used in Marietta et al. (2000) since the companion still do not reach thermal equilibrium because of mass transfer. The reduction of the stripped material in Meng, Chen & Han (2007) compared with that in Marietta et al. (2000) primarily results from the pre-explosion mass loss. The MS model in Meng, Chen & Han (2007) is from a more massive star experiencing a mass-loss phase before supernova explosion, which leads to a more compact companion star whose material is more difficult to strip than it is in a solar model as used in Marietta et al. (2000). Since Meng, Chen & Han (2007) did not consider the thermal energy imparted by the ejecta into the companion envelope, which likely heats and vaporizes a part of the envelope and thereby increases the amount of stripped material, $0.035 M_\odot$ should be a conservative lower limit. If enough hydrogen-rich materials are stripped, they should reveal themselves by narrow H$_\alpha$ emission or absorption line in late-time spectra of SNe Ia (Chugai 1984; Filippenko 1992). However, the H$_\alpha$ line was not detected and the amount of the stripped material was constrained to be less than $0.02 M_\odot$ by observations (Mattila et al. 2005; Leonard 2007), which is much smaller than $0.15 M_\odot - 0.17 M_\odot$ and is even smaller than the lower limit obtained by Meng, Chen & Han (2007). In addition, the simulation in Marietta et al. (2000) and Meng, Chen & Han (2007) showed that the luminosity of supernova companion after collision by supernova ejecta should dramatically rise to a level much higher than that of Tycho G by about three orders of magnitude.

Owing to the discussions above, a detailed numerical simulation on the interaction between supernova ejecta and its companion should be very important, while the subject is closely related with the properties of the secondaries before SNe Ia explosion. Recently, Meng, Chen & Han (2009) (hereinafter Paper I) calculated a dense grids of binary systems by detailed binary evolution for different metallicities and gave the initial parameters of the systems leading to SNe
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Ia in an orbital period-secondary mass \((\log P_i, M_2)\) plane. The aim of this paper is to, using the results in Paper I, show the properties of secondaries before and after the SNe Ia explosion, which can provide help to do detailed numerical simulations of the collision between supernova ejecta and its companion, and/or search the companion in the explosion remnant of a SN Ia.

The paper is organized as follow. We simply show our binary population synthesis (BPS) method in section 2 and the BPS results in section 3. In section 4, we briefly discuss our results and summarize the main conclusions in section 5.

**Figure 2.** Similar to Fig 1 but for \(Z = 0.01\) (Top) and \(Z = 0.004\) (Bottom).

2 BINARY POPULATION SYNTHESIS

2.1 The parameters of WD+MS systems leading to SNe Ia

Incorporating the prescription in \cite{Hachisu1999} on the accretion of the hydrogen-rich material from its companion onto a WD into the Eggleton’s stellar evolution code \cite{Eggleton1971, Eggleton1972, Eggleton1973}, \cite{Meng2009} calculated more than 25,000 binary evolutions of WD+MS channel. In the channel, a companion fills its Roche lobe in MS stage or in Hertzprung gap (HG) and transfers some of its mass onto the surface of the WD. As a consequence, the mass of the WD increases gradually. If the mass of the WD reaches \(\sim 1.378M_\odot\) \cite{Nomoto1984}, they assumed that the WD explodes as a SN Ia. \cite{Meng2009} provided the initial parameter spaces of the WD + MS systems leading to SNe Ia in an orbital period - secondary mass \((\log P_i, M_2)\) plane. Their calculations are comprehensive and systematical, and various properties of the companion stars with different metallicities were obtained but not sorted for publishing. In this paper,
we extract the properties from the data files of the calculations and incorporate them into the rapid binary evolution code developed by Hurley et al. (2000, 2002) to obtain the various properties of the companions at the moment of explosion.

### 2.2 Common envelope

Common envelope (CE) is very important for the formation of WD + MS systems. We firstly introduce the treatment for CE in this paper. Hereinafter, we use primordial to represent the stage before the formation of WD+MS systems and initial for WD+MS systems. During binary evolution, the primordial mass ratio (primary to secondary) is crucial for the first mass transfer. If it is larger than a critical mass ratio, $q_c$, the first mass transfer is dynamically unstable and a CE forms (Paczynski 1976). The ratio $q_c$ varies with the evolutionary state of the primordial primary at the onset of RLOF (Hjellming & Webbink 1987, Webbink 1988, Han et al. 2002, Podsiadlowski et al. 2002, Chen & Han 2008). In this study, we adopt $q_c = 4.0$ when the primary is on MS or HG. This value is supported by detailed binary evolution studies (Han et al. 2000, Chen & Han 2002, 2003). If the primordial primary is on FGB or AGB, we use

$$q_c = [1.67 - x + 2(M_{\text{pc1}}^{\text{r}}/M_{\text{pc1}}^{\text{p}})^{5/3})/2.13,$$

(1)

where $M_{\text{pc1}}^{\text{r}}$ is the core mass of primordial primary, and $x = d \ln R_{\text{pc1}}^{\text{r}} / d \ln M_{\text{pc1}}^{\text{p}}$ is the mass-radius exponent of primordial primary and varies with composition. If the mass donors (primaries) are naked helium giants, $q_c = 0.748$ based on equation (1) (see Hurley et al. 2002 for details).

**Figure 3.** Similar to Fig 1 but for $Z = 0.001$ (Top) and $Z = 0.0003$ (Bottom).

**Figure 4.** Similar to Fig 1 but for $Z = 0.0001$. Top: $\alpha_{\text{CE}} = 1.0$; Bottom: $\alpha_{\text{CE}} = 3.0$. Included here is the importance of the common envelope in the formation of WD + MS systems.
where $\Delta E_{\text{orb}}$ is the orbital energy released, $E_{\text{bind}}$ is the binding energy of common envelope, and $\alpha_{\text{CE}}$ is CE ejection efficiency, i.e. the fraction of the released orbital energy used to eject the CE. Since the thermal energy in the envelope is not incorporated into the binding energy, $\alpha_{\text{CE}}$ may be greater than 1 (see Han, Podsiadlowski & Eggleton 1993 for details about the thermal energy). In this paper, we set $\alpha_{\text{CE}}$ to 1.0 or 3.0.

### 2.3 Evolution channels

There are three channels to produce WD + MS systems according to the situation of the primary in a primordial system at the onset of the first RLOF.

**Case 1 (He star channel):** The primordial primary is in Hg or on RGB at the onset of the first RLOF (i.e. case B evolution defined by Kippenhahn & Weigert 1967). In this case, a CE is formed because of a large mass ratio or a convective envelope of the mass donor. After the CE ejection (if it occurs), the mass donor becomes a helium star and continues to evolve. The helium star likely fills its Roche lobe again after the central helium is exhausted. Since the mass donor is much less massive than before, this RLOF is dynamically stable, resulting in a close CO WD+MS system (see Nomoto et al. 1999, 2003 for details).

**Case 2 (EAGB channel):** The primordial primary is in early asymptotic giant branch stage (EAGB) (i.e. helium is exhausted in the core, while thermal pulses have not yet started). A CE is formed because of dynamically unstable mass transfer. After the CE is ejected, the orbit decays and the primordial primary becomes a helium red giant (HeRG). The HeRG may fill its Roche lobe and start the second RLOF. Similar to the He star channel, this RLOF is stable and produces WD + MS systems after RLOF.

**Case 3 (TPAGB channel):** The primordial primary fills its Roche lobe at the thermal pulsing AGB (TPAGB) stage. Similar to the above two channels, a CE is formed during the RLOF. A CO WD + MS binary is produced after CE ejection.

The WD + MS systems continue to evolve and the secondaries may also fill their Roche lobes at a stage and Roche lobe overflow (RLOF) starts. We assume that if the initial orbital period, $P_{\text{orb}}$, and the initial secondary mass, $M_2^i$, of a WD + MS system locate in the appropriate regions in the $(\log P^i, M_2^i)$ plane for SNe Ia at the onset of RLOF (see Paper I), a SN Ia is then produced. The properties of the binary system at the moment of SN explosion are obtained by interpolation in the three-dimensional grid $(M_{\text{WD}}, M_2^i, \log P^i)$ of the more than 25,000 close WD binary system calculated in Paper I.

### 2.4 Basic parameters in Monte Carlo simulation

To investigate the statistical properties of companions before and after explosion, we carry out a series of binary population synthesis (BPS) studies for various Z by Hurley’s rapid binary evolution code (Hurley et al. 2000, 2002) incorporating the results in Paper I. Since the code is only valid for $Z \leq 0.03$, only seven metallicities, i.e. $Z = 0.03, 0.02, 0.01, 0.004, 0.001, 0.0003$ and 0.0001, are examined here. In each BPS study, $10^7$ binaries are generated by Monte Carlo simulation and a circular orbit is assumed for all binaries. The basic parameters for the simulations are as follows.

(i) The initial mass function (IMF) of Miller & Scalo (1979) is adopted. The primordial primary is generated according to the formula of Eggleton et al. (1989): $M_1^p = \frac{0.19X}{(1-X)^{0.75} + 0.032(1-X)^{0.25}},$ where $X$ is a random number in the range $[0,1]$ and $M_1^p$ is the mass of the primordial primary, which ranges from 0.1 $M_\odot$ to 100 $M_\odot$.

(ii) The mass ratio of the primordial components, $q$, is a very important parameter for binary evolution while its distribution is quite controversial. For simplicity, we take a uniform mass-ratio distribution (Mazeh et al. 1992; Goldberg & Mazeh 1994):

$$n(q) = 1, \quad 0 < q < 1,$$

where $q = M_1^p/M_2^p$.

(iii) We assume that all stars are members of binary systems and that the distribution of separations is constant in log $a$ for wide binaries and falls off smoothly at close separation:

$$n(a) = \begin{cases} \alpha_{\text{sep}}(a/a_0)^m & a \leq a_0; \\ \alpha_{\text{sep}}, & a_0 < a < a_1, \end{cases}$$

where $\alpha_{\text{sep}} \approx 0.070$, $a_0 = 10 R_\odot$, $a_1 = 5.75 \times 10^6 R_\odot = 0.13$pc and $m \approx 1.2$. This distribution implies that the numbers of wide binary system per logarithmic interval are equal, and that approximately 50% of the stellar systems are binary systems with orbital periods less than 100 yr (Han, Podsiadlowski & Eggleton 1995).

(iv) We simply assume a constant star formation rate (SFR) over last 15 Gyr.

### 3 BINARY POPULATION SYNTHESIS RESULTS

#### 3.1 the companion masses and the orbital periods of WD + MS systems at the moment of explosions

The secondary masses and the periods of WD + MS systems at the moment of explosion are basic input parameters when one simulates the interaction between supernova ejecta and its companion. We show the distributions of the masses and the periods for different metallicities $Z$ in Figs. 3 to 4, where $M_{\text{WD}} = 1.378 M_\odot$. Here, we only show the cases of $\alpha_{\text{CE}} = 1.0$ except for $Z = 0.0001$ (see the bottom panel in Fig. 3). For other $Z$, $\alpha_{\text{CE}}$ does not significantly affect the final distributions.

From these figures, we see that generally, the companions with a high metallicity $Z$ have larger final masses, and roughly when $Z > 0.004$, the final periods center on 1 to 1.6 days, smaller than those of the cases of $Z \leq 0.004$ (centering on 2.5 to 6.5 days). These phenomena are mainly derived from the distributions of the initial parameters of WD +MS systems with various $Z$. Paper I has shown that a high metallicity leads to a more massive initial secondary mass(see Figs. 4 and 10 in Paper I), and the systems with $Z > 0.004$ have a shorter initial period than those with...
Z ≤ 0.004 (see Fig. 11 in Paper I). Meanwhile, metallicity also affects mass transfer process. A high metallicity results in a lower mass transfer rate (Langer et al. 2000), and then less material loses from binary system as optically thick wind (Hachisu et al. 1996), which means that more transferred materials are accumulated on the WD. Therefore, mass-ratio inversion for a WD + MS system with a high metallicity is delayed, and then the WD + MS system is more likely to decrease its orbital period, which may lead to a relatively low period (see also Paper I and Meng, Yang & Geng 2009).

The bottom panel in Fig. 4 shows the case for Z = 0.0001 and α_{CE} = 3.0. In the figure, there are two “islands” in the (M_{2}^SN, log P_{SN}) plane, i.e. a low-mass low-period one and a high-mass high-period one, which is significantly different from the top panel in Fig. 4. We have not found the two islands in other cases. As shown in subsection 2.2 and paper I, there are three channels leading to close WD + MS binary systems, i.e. He star channel, EAGB channel and TPAGB channel. Metallicity and α_{CE} may systemically affect the channels (see Paper I for the influence of Metallicity and α_{CE} on the channels for details). A low metallicity and a high α_{CE}, i.e. Z = 0.0001 and α_{CE} = 3.0, may result in double peaks in the distributions of the initial masses of CO WDs and the initial periods of WD + MS systems leading to SNe Ia (see Figs. 9 and 11 in Paper I). The low-mass peak and the low-period peak are from the EAGB channel, while the high-mass peak and the high-period peak are from the TPAGB channel. It is obvious that the low-mass peak of CO WDs and the low-period peak may lead to the low-mass low-period island in the bottom panel in Fig. 4, since more materials are needed to transfer onto CO WD from mass donor if a low-mass WD is adopted. For a similar reason, the high-mass high-period island in the bottom panel in Fig. 4 results from the high-mass peak and high-period peak from TPAGB channel.

When Z > 0.0001 and α_{CE} = 3.0, no WD + MS systems are from TPAGB channel, which results in the disappearance of double peaks (see Meng, Chen & Han 2009 for details). This can naturally explain why the double islands in Fig. 4 to the top panel in Fig. 4 disappear.

These figures may also help to check whether some binary system observed can explode as SNe Ia or not. In these figures, a recurrent nova, U Sco, is indicated by filled square (Schafer & Ringwald 1995; Hachisu et al. 2000b; ). The WD mass of U Sco is about 1.37M_{⊙}, and its companion is a MS sequence star of 1.5M_{⊙} (Hachisu et al. 2000b; ). The orbital period is 1.23056 days (Schafer & Ringwald 1995; Hachisu et al. 2000b; ). Hachisu et al. (1996) studied the system carefully and concluded that the WD mass can grow until an SN Ia explosion is triggered after ~ 10^5 yr. If the WD of U Sco may explode as a SN Ia finally, the companion should have a slightly smaller mass. Its period will decrease firstly, and then may increase if mass-ratio reverses. Then, its final position in (M_{2}^SN, log P_{SN}) plane will move to a lower mass from its present position at least, and may enters into the most probable area (see the bottom panel in Fig 1). From its present position in (M_{2}^SN, log P_{SN}) plane, it is very likely for U Sco to explode as a SN Ia (see also Hachisu et al. 2000; Meng, Yang & Geng 2007).

Figure 5. The distribution of the radii and the ratios of separations to radii of companions at the moment of supernova explosion for the case of α_{CE} = 1.0. Cross represents Tycho G, which is a potential candidate of the companion of Tycho’s supernova (Ruiz-Lapuente et al. 2004; Branch 2004). The length of the cross represents observational error. Solar symbol and star represent the main-sequence and subgiant companion model, respectively, which are applied to simulate the collision between supernova ejecta and its companion in Marietta et al. (2000). The position of a recurrent nova, U Sco, is indicated by the filled square (Schafer & Ringwald 1995; Hachisu et al. 2000b; ). Top: Z = 0.03; Bottom: Z = 0.02.

3.2 Radii and the ratios of separations to radii of companions at the moment of explosions

The radius of a companion, R_{2}^{SN}, and the ratio of separation to the companion’s radius, A/R_{2}^{SN}, at the moment of explosion are important parameters for simulating the interaction between supernova ejecta and the companion (Marietta et al. 2000). There is even a linear dependence of kick velocity and the mass of stripped material on log(A/R_{2}^{SN}) (Marietta et al. 2000, Meng, Chen & Han 2007). After the interaction, the companion reestablishes dynamical equilibrium quickly while it is still in a process into...
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Figure 6. Similar to Fig. 5 but for $Z = 0.01$ (Top) and $Z = 0.004$ (Bottom).

Figure 7. Similar to Fig. 5 but for $Z = 0.001$ (Top) and $Z = 0.0003$ (Bottom).

thermal equilibrium. The process into thermal equilibrium may last for $10^3 - 10^4$ yr. It is similar that a companion star is also not back into thermal equilibrium at the moment of supernova explosion since mass transfer is processing before supernova explosion. So, considering the amount of the stripped material from companions is small (see section I or next subsection, Mattila et al. 2005; Leonard 2007; Meng, Chen & Han 2007), the radius of a companion at the moment of supernova explosion may represent its radius after the impact of a SN Ia to some extent, and then our results can also compare with observation directly. Under the assumption that the radius of a companion is equal to its Roche lobe radius (Eggleton 1983), we show the distributions of $R_{SN}^2$ and $A/R_{SN}^2$ at the moment of explosion for various $Z$ and $\alpha_{CE} = 1.0$ in Figs. 5 to 8. The cases with $\alpha_{CE} = 3.0$ are similar to that with $\alpha_{CE} = 1.0$ except for $Z = 0.0001$ (the bottom panel in in Fig. 8).

The age of Tycho’s supernova is about 440 yr, which means that the suggested companion star of Tycho’s supernova, Tycho G, is still not back into thermal equilibrium and its radius at present might be similar to that at the moment of supernova explosion, also similar to its Roche lobe radius. Assuming that the radius of Tycho G at present is equal to its Roche lobe radius at the moment of supernova explosion, and using the equation in Eggleton (1983), we may obtain the $A/R_{SN}^2$ of Tycho G. The cross in the figures represents the Tycho G (Ruiz-Lapuente et al. 2004; Branch 2004). The solar symbol and open pentacle denote the MS (a solar model) and SG companion model, which are applied by Marietta et al. (2000) to simulate the interaction between supernova ejecta and its companion. Generally, the radius of a companion decreases with metallicity, which is directly originated from the dependence of the periods of systems on metallicity (see last subsection).

We see in these figures that Tycho G is consistent with our high-metallicity results. The SG companion model used in Marietta et al. (2000) also matches with our high-metallicity results since this model is obtained from Li & van den Heuvel (1997), who used a method and a stellar evolution code similar to that in Paper I with $Z = 0.02$. However, the MS model in Marietta et al. (2000) is obviously departed from the $(R_{SN}^2, A/R_{SN}^2)$ plane for all metal-
licities, which implies that a solar model is not a reasonable model when simulating the interaction between supernova ejecta and its companion.

There are also two islands in the \((R_{SN}^2, A/R_{SN}^2)\) plane with \(Z = 0.0001\) and \(\alpha_{CE} = 3.0\) (see the bottom panel in Fig. 8). The reason is same to that interpreted in subsection 3.1.

We also showed the recurrent nova, U Sco, in these figures. Since the orbital period of the system will reduce, the radius of the MS companion in the system should decrease, and \(A/R_{SN}^2\) increase based on the equation of Eggleton (1983). The position of U Sco will move towards right-lower region in \((R_{SN}^2, A/R_{SN}^2)\) plane, and may enter into the most probable region (see the bottom panel in Fig. 5). The bottom panel in Fig. 8 also shows that the recurrent nova, U Sco, probably explodes as a SN Ia.

Figure 8. Similar to Fig. 5 but for \(Z = 0.0001\). Top: \(\alpha_{CE} = 1.0\); Bottom: \(\alpha_{CE} = 3.0\).

Figure 9. The distribution of the masses and the space velocities of companions in SNe Ia remnant for \(Z = 0.03\) and \(\alpha_{CE} = 3.0\). The cross represents the position of Tycho G, which is the potential candidate of the companion of Tycho's supernova (Ruiz-Lapuente et al. 2004; Branch 2004), and the length of the bars of the cross represents observational error. The position of the MS star of a recurrent nova, U Sco, is indicated by the filled square, where its space velocity is its orbital velocity relative to the mass center of the system (Schaefer & Ringwald 1993; Hachisu et al. 2000b). Top: \(Z = 0.03\); Bottom: \(Z = 0.02\).

3.3 the masses and space velocities of companions in SNe Ia remnant

As mentioned in section 1, in the single-degenerate model, supernova ejecta collides into the envelope of its companion after SN Ia explosion and strips some hydrogen-rich material from the surface of the companion (Cheng 1974; Wheeler et al. 1974; Fryxell & Arnett 1981; Taam & Fryxell 1984; Chugai 1986; Liven, Tuchman & Wheller 1992; Marietta et al. 2000). Marietta et al. (2000) ran several high-resolution two-dimensional numerical simulation of the collision between supernova ejecta and its companion, where the companion is a MS star, a subgiant (SG) star, or a red giant.
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Figure 10. Similar to Fig. 9 but for $Z = 0.01$ (Top) and $Z = 0.004$ (Bottom).

(MG) star. They found that the hydrogen-rich material of at least $0.15 M_\odot$ is stripped from the envelope of a companion. However, Meng, Chen & Han (2007) used a simple analytic method while a more physical companion model than that of Marietta et al. (2000) to simulate the collision and found that the stripped material may be as low as $0.035 M_\odot$. Observationally, Mattila et al. (2005) and Leonard (2007) showed that the amount of stripped hydrogen rich material is less than $0.02 M_\odot$ which can be neglected in comparison with companion mass. After the collision, the companion gains a kick velocity, which is much lower than the orbital velocity of the companion (Marietta et al. 2000; Meng, Chen & Han 2007).

For the reasons above, we assume that the mass of a companion is not changed by the collision of supernova ejecta and its space velocity after the collision is equal to its orbital velocity at the moment of explosion. Figs. 1 to 4 present the distributions of the masses and the space velocities of companions in SNe Ia remnant for different metallicities. Observationally, mass can be deduced from the spectral type of a star combining with the star’s surface gravity and luminosity, and space velocity can be obtained from proper motion and radial velocity combining with distance. Then, our results can be compared with observations. The cross in the figures represents the position of Tycho G, which is a potential candidate of the companion of Tycho’s supernova (Ruiz-Lapuente et al. 2004; Branch 2004; Hernández et al. 2009). It is interesting that the position of Tycho G is well consistent with our high-metallicity results, although Tycho G was suspected not to be the companion of Tycho’s supernova (Fuhrmann 2005; Ihara et al. 2007).

We see in the figures that the masses and the space velocity both increase with metallicity on average, which is derived from the dependence of the final secondary mass and the final period on metallicity as shown Figs. 1 to 4.

The bottom panel in Fig. 12 shows the $(M_{SN}^2, V)$ plane for $Z = 0.0001$ and $\alpha_{CE} = 3.0$. There are also two islands in the figure. The low-mass high-velocity one is from EAGB channel and the high-mass low-velocity island is from TPAGB channel. The reason is same to that interpreted in subsections 3.1.4.

In these figures, we also show the position of the MS
3.4 The distribution of the gravities of companions

The surface gravity of the companion in a SN Ia remnant is another parameter which can be directly obtained from spectral observations (Ruiz-Lapuente et al. 2004). Surface gravity will be changed by the impact of supernova ejecta. As depicted in subsection 3.2, companions after the impact of supernova ejecta are processing into thermal equilibrium. Meanwhile, the thermal equilibrium of companions is still not reestablished at the moment of supernova explosion for pre-explosion mass transfer. Considering the insignificant change of companion mass, the surface gravity of a companion at the moment of explosion may represent a real one after the interaction to some extent, and then we could make a comparison between the distribution of the calculated surface gravities of companions and observations. We show the distributions of the surface gravities at the moment of explosion for various $Z$ and $\alpha_{CE} = 3.0$ in Fig. 13. $\alpha_{CE}$ does not significantly change the distributions expect for $Z = 0.0001$. Double peaks also appear for the case of $Z = 0.0001$ in the figure. The low-gravity peak is from the TP AGB channel and the high-gravity one is from the EAGB channel. We see from the figure that the surface gravity for high-metallicity stars are generally larger than that for low-metallicity ones, which is directly derived from the larger masses and smaller radii of the companions with a high $Z$. Most stars have surface gravity $\log g$ in the range of 2-5. The potential companion of Tycho’s supernova, Tycho G, has a surface gravity $\log g$ between 3.0 and 4.0 (Ruiz-Lapuente et al. 2004). Seen from the figure, it is difficult to judge the metallicity of Tycho G based on its surface gravity.

Figure 13. The distribution of the gravities of companions for different metallicities with $\alpha_{CE} = 3.0$, where the gravities are in cm/s$.^2$. 

Figure 14. The distribution of the opening angles of the holes in SNe Ia remnant for different metallicities with $\alpha_{CE} = 3.0$. 

Figure 12. Similar to Fig. 9 but for $Z = 0.0001$. Top: $\alpha_{CE} = 1.0$; Bottom: $\alpha_{CE} = 3.0$. 

star of the recurrent nova U Sco, where its space velocity is its orbital velocity relative to the mass center of the system. The fate of U Sco as a SN Ia is also clearly shown in the bottom panel of Fig. 9.
3.5 Percentage of SNe Ia with polarization spectrum

After the interaction between supernova ejecta and its companion, the companion star carves out a conical hole of opening angle $30^\circ - 40^\circ$ in the supernova ejecta and the hole will never disappear because the ejecta are moving superno-

cally (Marietta et al. 2000). The aspheric configuration of supernova ejecta may reveal itself by polarization spectrums near maximum light (Kasen et al. 2004). With the advance of spectropolarimetric observations, the nature of SN Ia asphericity becomes an important relevant test of the single degenerate progenitor scenario (Wang & Wheeler 2008). Kasen et al. (2004) studied the effect of the hole on the spectra of SN Ia near maximum light and found that if the opening angle is larger than 20°, polarization spectrum may be obtained from any viewing angle. Considering the limit of spectropolarimetric observations (polarization should be larger than 0.2%), Leonard et al. (2003), a polarization spectrum can be detected when viewing angle is smaller than $120^\circ$ (defining that the viewing angle down the hole is $0^\circ$).

The opening angle of the hole, $\theta$, in a SN Ia remnant is mainly determined by $A/R_{SN}^2$ (Marietta et al. 2000). We use

$$\theta = 66.82 - 9.285(A/R_{SN}^2) + 0.3784(A/R_{SN}^2)^2$$

(6)

to calculate the opening angle of the hole. The equation is fitted from the half-mass angle of the distribution of stripped material given by Marietta et al. (2000) and the error of the equation is less than 1%. Note that the half-mass angle may be different from the opening angle and equation (6) may overestimate the opening angle by about 5°. Here, we assume that equation (6) is valid for all metallicities since metallicity may not significantly affect the interaction between supernova ejecta and its companion (Meng, Chen & Han 2007).

Fig. 14 show the distribution of the opening angles of the holes in SNe Ia remnants for different metallicities with $\alpha_{CE} = 3.0$. The results of $\alpha_{CE} = 1.0$ are similar to those of $\alpha_{CE} = 3.0$ expect for the case of $Z = 0.0001$. Double peaks also appear in Fig. 14 where the high-$\theta$ peak is from the TPAGB channel and the low-$\theta$ peak is from the EAGB channel. We see in the figure that the opening angles of the holes in all SNe Ia remnants are always larger than 20° even if the overestimate by equation (6) is considered. We assume that only when the view angle is smaller than $120^\circ$, polarization can be detected. Then, the percentage of SNe Ia with polarization spectrum is $1 - \frac{1 - \cos 60^\circ}{2} = 0.75$.

4 DISCUSSIONS

4.1 Tycho G

It is believed that SN Ia is from the thermonuclear runaway of a CO WD in a binary system. The CO WD accretes material from its companion to increase its mass. When its mass reaches its maximum stable mass, it explodes as a thermonuclear runaway and almost half of the WD mass is converted into radioactive nickel-56 (Branch 2004). Two progenitor models of SNe Ia have competed for about three decades. One is a single-degenerate model, which is widely accepted (Whelan & Iben 1973).

In this model, a CO WD increases its mass by accreting hydrogen- or helium-rich matter from its companion, and explodes when its mass approaches the Chandrasekhar mass limit. The companion may be a main-sequence star (WD+MS) or a red-giant star (WD+RG) (Yungelson et al. 1993; Li & van den Heuvel 1997; Hachisu et al. 1999a,b; Nomoto et al. 1999b; Langer et al. 2000). Between the two channels, WD + MS model is widely studied and some observations also uphold the channel (Hachisu et al. 1999a,b; Nomoto et al. 1999b; Langer et al. 2000; Han & Podsiadlowski 2004; Paper I). Hachisu & Kato (2003a,b) suggested that supersoft X-ray sources (SSSs) may be good candidates for the progenitors of SNe Ia, where some of SSSs belong to WD+MS channel. Recently, Hachisu & Kato (2005, 2006a,b) and Hachisu et al. (2007) showed that several recurrent novae is possibly the progenitor of SNe Ia and some of them belong to the WD+RG channel. Observationally, Patat et al. (2007) suggested that the companion of the progenitor of SN 2006X were an early RGB star. However, Hachisu et al. (2008) argued a WD + MS nature for this SN Ia. Considering a smaller calculated Galactic birth rate of SNe Ia from WD + MS channel than that derived observationally (Han & Podsiadlowski 2004; Paper I) and some WD + RG systems as the candidates of SNe Ia progenitors (Hachisu & Kato 2006a,b; Hachisu et al. 2007; Parthasarathy et al. 2007), WD + RG channel should be carefully investigated further although some BPS results showed a small contribution of WD + RG channel to the birth rate of SNe Ia (Yungelson & Livio 1993; Han & Podsiadlowski 2004). The other progenitor model of the SNe Ia is a double degenerate model (DD, Iben & Tutukov 1984; Webbink 1984), in which a system consisting of two CO WDs loses orbital angular momentum by gravitational wave radiation and merges. The merger may explode if the total mass of the system exceeds the Chandrasekhar mass limit (see the reviews by Hillebrandt & Niemeyer 2000 and Leibundgut 2000). The birth rate calculated from this channel was comparable with the observational rate (Han 1998; Yungelson & Livio 1993; 2004; Tutukov & Yungelson 2002). SN 2003fg and SN 2005bi is likely the cases from the DD channel (Howell et al. 2006; Branch 2006; Quimby, Höflich & Wheeler 2006). In addition, KPD 1930+2752 may be an excellent candidate of DD SN Ia progenitor, whose total mass ($\sim 1.52 M_\odot$) exceeds the Chandrasekhar mass limit and whose orbital shrinkage caused by gravitational wave radiation will lead to the merger of the binary in about 200 Myr, much smaller than the Hubble time (Geier et al. 2007). However, please pay attention that Ergma, Fedorova & Yungelson (2001) argued that, from detailed binary evolution calculation, the final mass of KPD 1930+2752 is smaller than the Chandrasekhar mass limit due to a large amount of mass loss during evolution.

A good way of discriminating between the many SN Ia progenitor scenarios is to search the companion of a SN Ia in its remnant. Unless the companion is another WD (DD channel, in which it has been destroyed by the mass-transfer process itself before explosion), it survives and shows some special properties in its spectra, which is originated from the contamination of supernova ejecta (Marietta et al. 2004). Ruiz-Lapuente et al. (2004; Branch 2004). Tycho’s supernova, which is one of only two SNe Ia observed in our Galaxy,
provides an opportunity to address observationally the identification of the surviving companion. [Ruiz-Lapuente et al. (2004)] searched the region of the remnant of Tycho’s supernova and suggested that Tycho G, a sun-like star, is the companion of Tycho’s supernova. Although, [Hara et al. (2007)] argued that the spectrum of Tycho G does not show any special properties, which seems to exclude the possibility of Tycho G to be the companion of Tycho’s supernova, the analysis of the chemical abundances of the Tycho G upholds the companion nature of the Tycho G ([Hernández et al. 2005]).

Interestingly, some integral properties of Tycho G, i.e., the mass, the space velocity, the radius and the surface gravity, are all consistent with our binary population synthesis results (see Figs. 3 and 13). Then, Tycho G is very likely to be the companion of Tycho’s supernova (see also Meng, Yang & Geng 2009). If Tycho G were the companion of Tycho’s supernova as shown by our BPS results, it would challenge one’s understanding about the physics of SNe Ia, such as the interaction between SNe Ia ejecta and companions.

4.2 The simulation of the interaction between SNe Ia ejecta and companions

In section 4.1 we have shown that Marietta et al. (2000) ran several high-resolution two-dimensional numerical simulations of the collision between the ejecta and the companion. They claimed that about 0.15 – 0.17M⊙ of hydrogen-rich material is stripped from a MS or a SG companion. They also found that in a sense of the collision, there is no difference whatever the companion is a MS star or a SG star. However, their results did not obtain confirmation by observations [Mattila et al. 2003; Leonard 2007]. Meng, Chen & Han (2007) used a simple analytic method to simulate the interaction between SNe Ia ejecta and companions and found that for a given condition, more hydrogen-rich material is stripped from a SG companion than that of a MS companion. To discuss the validity of their method, they repeated their work using the same method in their paper and the companion model in Marietta et al. (2000), and found that the result of SG model is similar to that in Marietta et al. (2000), while the amount of the stripped hydrogen-rich material of MS model is much smaller than that in Marietta et al. (2000). The reason of the difference is that the SG model in Marietta et al. (2000) is from Li & van den Heuvel (1997), who used a method and a stellar evolution code similar to that in Paper I. However, the MS model in Marietta et al. (2000) is a solar model, which is not a typical case (see Figs 6 to 8). Meng, Chen & Han (2007) claimed that the difference of the results between their analytic method and the numerical simulation in Marietta et al. (2000) is mainly derived from the different stellar structure of the companion. Thermal equilibrium is not reestablished for the companion star at the moment of supernova explosion since the mass transfer is still processing before supernova explosion. Additionally, Marietta et al. (2000) and Meng, Chen & Han (2007) argued that the luminosity of a companion after the impact of SNe Ia ejecta would rise sharply to about 5000 L⊙, which is too high to compare with that of Tycho G. Therefore, considering that the properties of Tycho G is consistent with our BPS results, a detailed numerical simulation about the interaction between supernova ejecta and its companion should be encouraged by a more physical companion model than that in [Marietta et al. 2000].

Recently, Pakmor et al. (2008) used a more physical companion model and similar numerical simulation to that in [Marietta et al. 2000] to recalculate the interaction between supernova ejecta and companion. They found a similar result to that in [Marietta et al. 2000], and at the same time they claimed that under some special situation, results consistent with observation may be obtained, and then they claimed that theory does not conflict with observation. Based on the result in [Pakmor et al. 2008], if A/R2SN is smaller than 6, the amount of stripped mass from companions should be larger than 0.02 M⊙. According to the results in this paper (see figures 5 to 8), A/R2SN is always smaller than 6, and then the range of the stripped mass is from 0.07 M⊙ to 0.16 M⊙, which is consistent with the results of Marietta et al. (2000) and Meng, Chen & Han (2007). The effort of Pakmor et al. (2008) then do not overcome the confliction between theory and observations (Mattila et al. 2003; Leonard 2007). The impact of a SN Ia on its companions still should be studied carefully. Maybe, unsymmetrical explosion plays an important role [Plewa et al. 2004].

4.3 Polarization of SNe Ia

As an important diagnostic tool for discriminating among SN Ia progenitor systems and theories of the explosion physics, spectropolarimetry provides the direct probe of early-time SN geometry. The essential idea is as follows: electron scattering dominates a hot young SN atmosphere and its nature is highly polarizing. For an unresolved source with a spherical distribution of scattering electrons, the directional components of the electric vectors of the scattered photons cancel exactly, yielding zero net linear polarization. An incomplete cancellation will be derived from any asymmetry in the distribution of the scattering electrons, or of absorbing material overlying the electron-scattering atmosphere. Then, a net polarization is expected [Leonard & Filippenko 2003; Wang & Wheeler 2008]. Single-degenerate model provides a natural way to produce the asymmetry. The exist of a companion may change the configuration of supernova ejecta and a polarization spectrum is expected. In this paper, we use the results of Marietta et al. (2000) and Kasen et al. (2004) to calculate the percentage of SNe Ia with polarization spectrum and found that about 75% of all SN Ia may be detected by spectropolarimetry. However, this result critically depends on the following assumptions: (i) all SNe Ia are from single-degenerate progenitor systems, (ii) Marietta et al. (2000) showed reliable simulations in the sense that a hole is indeed formed and does not quickly close with time and (iii) Kasen et al. (2004) provided a reasonable simulation of polarization spectrum resulted from the exist of a hole in a supernova ejecta.

It is likely that the single-degenerate model is only one of the reliable models, such as the prompt component in the two-component model suggested by Scannapieco & Bildsten (2003) and Mannucci et al. (2004). At present, any definitive conclusion about DD model is premature, and this scenario can naturally result in an asymmetry of distribution of supernova ejecta. One mechanism is the rapid rotation
of a WD before supernova explosion, which leads to the change of the stellar shape. Another one is that there may be a thick accretion disk around CO WD and the disk is an origin of the asymmetry of the configuration of supernova ejecta (see the reviews by Hillebrandt & Niemeyer 2000 and Leibundgut 2001 for details about DD model). Additionally, explosion mechanism itself may also produce the asymmetry and a polarization spectrum is expected [Plewa et al. 2004; Kasen & Plewa 2003]. Then, it is probable that the percentage of SNe Ia with polarization spectrum estimated in this paper is a lower limit. At present, almost all SNe Ia, which are observed by spectropolarimetry, had various degrees of polarization signal [Leonard et al. 2003].

4.4 The percentage of SN 1991T-like

SN 1991T is an overluminous event and has a rather broad light curve ($\Delta m_{15} = 0.95 \pm 0.05$, where $\Delta m_{15}$ is the magnitude difference between its maximum and 15 days later Phillips et al. 1991), which is often taken as an indication of a large $^{56}$Ni mass (Hofflich et al. 1995; Nugent et al. 1997; Pinto & Eastman 2001). Its spectrum also showed some special properties, i.e. dominated by FeII and FeIII lines at maximum light, while the spectrum of a normal SN Ia is dominated by SiII line. A large $^{56}$Ni mass may well explain the peculiar spectral appearance (Jeffery et al. 1992; Mazzali et al. 1995). Nevertheless, Kasen et al. 2004 suggested a second, physically very different route to explain the spectral peculiarities of SN 1991T — one could be peering down an ejecta hole. They found that their synthesis spectrum down the ejecta hole can be comparable with that of SN 1991T-like supernovae is from 13% to 14% for different metallicities by assuming that if view angle is smaller than the opening angle of the hole in a SN Ia ejecta, the SN Ia show properties of SN 1991T-like. The opening angle is from Fig. 14. The calculated birth rate of SN 1991T-like supernovae is from 13% to 14% for different metallicities. The rate slightly increase with $Z$ and is a little larger than the estimation by Kasen et al. 2004 (~ 12%). Both Branch (2001) and Li et al. 2001 gave the observed rate of SN 1991T-like from 3% to 5%. If taking SN 1999aa-like as SN 1991T-like events, the birth rate of SN 1991T/SN 1999aa-like is $20\% \pm 7\%$ [Li et al. 2001]. Our results match with that of Li et al. 2001 within errors. So, it is possible that SNe Ia-like have not any special properties in physics except for the viewing angle of an observer.

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5 SUMMARY AND CONCLUSION

Incorporating the results of Meng, Chen & Han (2009) into Hurley’s rapid binary evolution code, we have carried out a series of binary population synthesis calculation and systematically the properties of the companions of SNe Ia for different $Z$ at the moment of explosions. We give the distributions of the masses, $M_{2}^{SN}$, the radii, $R_{2}^{SN}$, of companions and the periods, $P_{SN}$ and the ratios of separations to radii, $A/R_{2}^{SN}$, of final binary systems for various $Z$ at the moment of supernova explosion and find that generally, $M_{2}^{SN}$ increases and $R_{2}^{SN}$ and $P_{SN}$ decrease with $Z$, while the distributions of $A/R_{2}^{SN}$ are similar for all metallicities. These parameters can be applied to constrain the numerical simulation of the interaction between the ejecta of a supernova and its companion. In addition, these parameters can help to judge whether a WD + MS system may explode as a SN Ia or not. We also show the distributions of some integral properties, i.e. the masses, the radii, the surface gravities and the space velocities of companions for different $Z$ after the interaction. The distributions can provide help to search companion in supernova remnant. Especially, some integral properties of Tycho G (a potential candidate of the companion of Tycho’s supernova), such as mass, radius, surface gravity and space velocity, well match with our BPS results. This fact may challenge our understanding about the physics of SNe Ia, especially the interaction between supernova ejecta and its companion. Using the results simulated by Marietta et al. (2000) and Kasen et al. (2004), we find that about 75% of all supernovae can be detected by spectropolarimetric observations. If considering that there may be different progenitor models of SNe Ia and different explosion mechanisms, the percentage could increase.
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