WIND-DRIVEN EVOLUTION OF WHITE DWARF BINARIES TO TYPE Ia SUPERNOVAE

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Received 2013 October 23; accepted 2013 November 20; published 2013 December 13

ABSTRACT

In the single-degenerate scenario for the progenitors of Type Ia supernovae (SNe Ia), a white dwarf rapidly accretes hydrogen- or helium-rich material from its companion star and appears as a supersoft X-ray source. This picture has been challenged by the properties of the supersoft X-ray sources with very low mass companions and the observations of several nearby SNe Ia. It has been pointed out that the X-ray radiation or the wind from the accreting white dwarf can excite winds or strip mass from the companion star, thus significantly influencing the mass transfer processes. In this paper, we perform detailed calculations of the wind-driven evolution of white dwarf binaries. We present the parameter space for the possible SN Ia progenitors and for the surviving companions after the SNe. The results show that the ex-companion stars of SNe Ia have characteristics more compatible with the observations, compared with those in the traditional single-degenerate scenario.

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

Online-only material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are among the most luminous explosions in the observable universe (Filippenko 1997). The cosmological precision distance measurements enabled by SNe Ia first revealed the accelerating expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999). The general consensus holds that SNe Ia arise from the thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) in close binaries (Hoyle & Fowler 1960; Nomoto 1982; Iben & Tutukov 1984; Nomoto et al. 1997).

The mainstream progenitor models of SNe Ia can be categorized as the single-degenerate (SD) and the double-degenerate (DD) scenarios (for reviews, see Branch 1998; Podsiadlowski 2010; Wang & Han 2012). In the SD scenario, a CO WD accretes hydrogen-/helium-rich material from its stellar companion until its mass approaches the Chandrasekhar mass $M_{\text{Ch}} = 1.38 M_\odot$ (Welan & Iben 1973; Nomoto 1982; Munari & Renzini 1992; Hachisu et al. 1996; Li & van den Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004; Ivanova & Taam 2004; Lü et al. 2009; Wang et al. 2010). The DD scenario involves two WDs in a close binary; the merger of the two WDs, which have masses larger than or equal to $M_{\text{Ch}}$, may result in a Type Ia supernova (Tutukov & Yungelson 1981; Iben & Tutukov 1984; Webink 1984; Yungelson et al. 1994). In addition, Kashi & Soker (2011) suggest that during the final stages of common envelope (CE) evolution, a merger of a WD with the core of an asymptotic giant branch or a red giant branch star may trigger a SN Ia, which is termed the core-degenerate scenario. Observational and theoretical evidence exists both for and against each of the progenitor scenarios. At present, it is unclear whether any of these possibilities is exclusively realized in nature or whether both contribute to SNe Ia (e.g., Howell 2011).

In this work, we focus on the SD scenario, which is observationally manifested by the supersoft X-ray sources (SSSs). In these sources, a WD is thought to be accreting rapidly from its binary companion (Kahabka & van den Heuvel 1997). Van den Heuvel et al. (1992) explained the observed characteristics of SSSs by steady nuclear burning of hydrogen on the WDs. In this model, mass is transferred from a main sequence (MS) or (sub)giant donor star on a thermal or nuclear timescale by Roche lobe overflow (RLOF). For steady hydrogen burning, the accretion rate should be $\gtrsim 10^{-7} M_\odot \text{yr}^{-1}$ for a $1 M_\odot$ WD. Binary evolutionary calculations show that the donor star is either a MS star more massive than the WD (with mass $\sim 2$ -- $3.5 M_\odot$) or a low-mass ($\sim 1 M_\odot$) (sub)giant star (e.g., Rappaport et al. 1994; Hachisu et al. 1996; Li & van den Heuvel 1997; Yungelson et al. 1996; Langer et al. 2000; Wang et al. 2010), to ensure that the mass transfer rate is high enough for steady burning.

A number of observational results have been used to constrain the SN Ia progenitor models, including the surviving companion stars of SNe Ia, the signatures of gas outflows from the SNe Ia progenitor systems, the early multi-wavelength emission of SNe Ia, the stripped mass of the companions due to SN explosions, etc. (see Wang & Han 2012, and references therein). In particular, the delay time distribution (DTD) of SNe Ia presents a useful tool to probe the progenitor scenarios. From studies using various SN samples, environments, and redshift ranges, a best fit power-law form $t^{-1}$ has been derived, in which a similar DTD with prompt (a few $10^8$ yr), delayed, and intermediate (a few gigayears) components was recovered (see Maoz & Mannucci 2012 for a review). This requires that in the SD scenario the donor mass be in the range of $1 M_\odot$ to $\sim 7 M_\odot$, considerably wider than predicted by the aforementioned investigations. However, it is well known that when the donor mass is more massive than $(3-4) M_\odot$, the mass transfer is dynamically unstable and a CE stage must follow. Moreover, the observational properties of some SSSs (e.g., RX J0439.8−6809, 1E0035.4−7230, RX J0537.7−7034, and CAL 87) do not fit in the classical picture of SSSs being driven by thermal timescale mass transfer. For example, the high luminosity ($\sim 10^{37}$ erg s$^{-1}$) and low temperature ($\sim 5 \times 10^3$ K) measured in 1E0035.4−7230 establish that it is a supersoft binary that has a WD with stable nuclear burning. However, the orbital period of 4.126 hr (Schmidtk et al. 1996) is significantly shorter than that required for a binary with thermal timescale mass transfer and implies a mass ratio $M_2/M_1 \lesssim 0.7$ (where $M_1$ and $M_2$ are the masses of the WD and the donor, respectively;
van Teeseling & King (1998). It is also interesting to note that the prototype SSS CAL 87 has a WD of mass 1.35 $M_\odot$ ( Starrfield et al. 2004) in a 10.6 hr orbit ( Nayl or et al. 1989; Callanan et al. 1989). The donor masses and orbital periods in these systems are in contradiction with the standard picture of SSSs.

To resolve the above inconsistencies, a wind-driven evolution of SSSs was proposed in the literature. There are two kinds of such models in which the “wind” has different meaning and operates in different ways. In relatively low-mass systems, van Teeseling & King (1998) and King & van Teeseling (1998) suggest that the companion star can be irradiated by the soft X-rays from the SSS, exciting strong winds that drive RLOF at a high rate and sustain steady hydrogen burning on the accreting WD. For relatively massive systems, Hachisu et al. (2008a) propose that the optically thick winds from the accreting WD can collide with the companion and strip off its surface layer. This mass stripping attenuates the mass transfer rate, thus preventing the formation of a CE. Hachisu et al. (2008b) showed that the predicted DTD from (1998) and Hachisu et al. (2008a) use das e m i - binaries, including the wind effect. In Section 2, we introduce the evolution of WD binaries. In this paper, we present detailed analytical method or semi-empirical input to investigate the formation of a CE. Hachisu et al. (2008b) showed that the mass stripping from the donor due to the WD’s wind escaping the system (for details, see King & van Teeseling 1998). Stability analysis shows that, for SSSs with a low mass ratio ($\lesssim 1$), the resulting mass transfer is stable and with a rate sufficient to keep the binary in the stable (steady or recurrent) hydrogen burning regime; for WD binaries with large mass ratios ($\gtrsim 1$), the self-excited winds can stabilize mass transfer at a threshold value ($\sim 10^{-8} M_\odot$ yr$^{-1}$) for nonexplosive nuclear burning of the accreted matter (King & van Teeseling 1998).

2. THE WIND-DRIVEN MODELS

We calculate the evolution of a binary consisting of a WD and a MS companion star with an updated version of Eggleton’s stellar evolution code ( Eggleton 1971, 1973). We take into account the self-excited winds from the donor due to the irradiation from the WD (termed case 1; King & van Teeseling 1998), the mass stripping from the donor due to the WD’s wind (termed case 2; Hachisu et al. 2008a), and the response of the donor due to the related mass loss processes. Beside angular momentum losses due to the winds or the stripped material, angular momentum loss caused by gravitational wave radiation (Landau & Lifshitz 1975) and magnetic braking (Verbunt & Zwaan 1981; Rappaport et al. 1983) is also considered. Below, we introduce the self-excited wind model and the mass-stripping model.

2.1. The Self-excited Wind Model

Van Teeseling & King (1998) argue that irradiation in perhaps all SSSs may lead to a strong stellar wind from the heated side of the donor star. If the wind escapes the binary with the specific angular momentum of the donor, it will drive mass transfer with a rate that is of the same order as the wind loss rate. The relation between the mass transfer rate $\dot{M}_\text{tr}$ and the wind loss rate $\dot{M}_\text{w}$ obeys

$$\dot{M}_\text{w} \simeq 3.5 \times 10^{-7} M_\odot \text{yr}^{-1} \left( \frac{M_2}{M_\odot} \right)^{5/6} \left( \frac{M}{M_\odot} \right)^{-1/3} \left( \frac{\eta_s \eta_a}{\dot{M}_\text{tr}} \right)^{1/2} \phi \left( \frac{\dot{M}_\text{tr}}{10^{-7} M_\odot \text{yr}^{-1}} \right)^{1/2} \quad (1)$$

for $M_2 \lesssim M_1$ and

$$\dot{M}_\text{w} \simeq 3.5 \times 10^{-7} M_\odot \text{yr}^{-1} \left( \frac{M_2}{M_\odot} \right)^{0.95} \left( \frac{M}{M_\odot} \right)^{-1/3} \left( \frac{\eta_s \eta_a}{\dot{M}_\text{tr}} \right)^{1/2} \left( \frac{\dot{M}_\text{tr}}{10^{-7} M_\odot \text{yr}^{-1}} \right)^{1/2} \quad (2)$$

for $M_2 \gtrsim M_1$. Here, $M = M_1 + M_2$ and $\eta_s$ measures the efficiency of the WD’s spectrum at producing ionizing photons. Normalized to the case of supersoft X-ray temperatures of a few times $10^5$ K, $\eta_s$ measures the luminosity per gram of matter accreted relative to the value for hydrogen shell burning and $\phi$ is an efficiency factor parameterizing the fraction of the companion’s irradiated face and the fraction of the wind mass escaping the system (for details, see King & van Teeseling 1998). Stability analysis shows that, for SSSs with a low mass ratio ($\lesssim 1$), the resulting mass transfer is stable and with a rate sufficient to keep the binary in the stable (steady or recurrent) hydrogen burning regime; for WD binaries with large mass ratios ($\gtrsim 1$), the self-excited winds can stabilize mass transfer at a threshold value ($\sim 10^{-8} M_\odot$ yr$^{-1}$) for nonexplosive nuclear burning of the accreted matter (King & van Teeseling 1998).

2.2. The Mass-stripping Model

Hachisu et al. (2008a) introduce the mass-stripping effect on a MS or slightly evolved companion star by the winds from an accreting WD. Since the companion star is initially more massive than the WD, mass transfer proceeds on a thermal timescale. If the mass transfer rate exceeds the critical rate (e.g., Nomoto 1982),

$$\dot{M}_\text{tr} = 7.2 \times 10^{-6} (M_{\text{WD}}/M_\odot - 0.6) M_\odot \text{yr}^{-1}, \quad (3)$$

there is optically thick wind to blow from the WD (Hachisu et al. 1996). The fast-moving wind collides with the companion star and strips off its surface layer by the shock dissipated into it (Hachisu & Kato 2003). The stripping rate is estimated to be

$$\dot{M}_\text{strip} = C_1 \dot{M}_\text{wind}, \quad (4)$$

where $C_1$ is a numerical factor determined by the binary separation and the masses of both components, with a value ranging $\sim 1-10$, and $\dot{M}_\text{wind}$ is the wind loss rate from the WD. The stripped mass is assumed to leave the binary from the $L_1$ point, carrying away the corresponding specific angular momentum. Since this mass stripping quickly decreases the mass of the donor star, it can attenuate the mass transfer rate, thus preventing the formation of a CE. In this way, young and massive companion stars can drive the WDs to SNe Ia explosions.

2.3. Growth of the WD Mass

The mass growth rate of the WD as a result of accretion is determined by the summed efficiencies of hydrogen and helium burning,

$$\dot{M}_{\text{WD}} = \eta_\text{H} \eta_\text{He} \dot{M}_\text{tr}, \quad (5)$$

where $\eta_\text{H}$ and $\eta_\text{He}$ represent the fraction of transferred hydrogen- and helium-rich matter from the companion that eventually burns into helium- and carbon-rich matter and stays on the WD, respectively. Here, we fit the numerical results of Prialnik & Kozovit (1995) and Yaron et al. (2005) for the hydrogen mass accumulation efficiency $\eta_\text{H}$ and adopt the prescriptions in Kato & Hachisu (2004) for the helium mass accumulation efficiency $\eta_\text{He}$.

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Figure 1. Solid lines outline the distributions of the initial orbital periods and companion masses of the progenitors of SNe Ia in case 1. The dashed lines are for no-wind evolution.

(A color version of this figure is available in the online journal.)

3. RESULTS

We have calculated the evolutions of a grid of binaries with WDs of initial mass $M_{\text{WD},i} = 1.0 M_\odot$–1.2 $M_\odot$ and MS companion stars of initial mass $M_{2,i} = 0.6 M_\odot$–7 $M_\odot$ with solar abundances in cases 1 and 2, respectively.

Figure 1 shows the distribution of the initial companion’s mass $M_{2,i}$ versus the initial orbital period $P_{\text{orb},i}$ in which the binaries can evolve to SNe Ia in case 1. The black, red, and blue solid lines correspond to the initial WD mass of 1 $M_\odot$, 1.1 $M_\odot$, and 1.2 $M_\odot$, respectively. The dashed lines show the results with the same WD mass but without self-excited winds considered, as calculated by Li & van den Heuvel (1997). In the latter case, the mass transfer is driven only by the nuclear evolution of the companion star. To acquire a sufficiently high mass transfer rate, the companion star should be more massive than $\sim 2 M_\odot$. When the self-excited wind from the companion star is included, the companion star’s mass can extend down to $\lesssim 1 M_\odot$. Since the wind can cause the orbit to shrink and accelerate the mass transfer, the mass transfer can maintain a rate high enough for stable burning, even if $M_2$ is not larger than $M_1$. However, this effect also lowers the upper limit of the companion’s mass and narrows the initial orbital period to some extent, because the mass transfer becomes dynamically unstable if $M_{2,i}$ or $P_{\text{orb},i}$ is larger.

The initial $M_{2,i}$ versus $P_{\text{orb},i}$ distributions in case 2 (with $C_1 = 3$) are shown in Figure 2(a). Figure 2(b) shows the same distribution but with fixed $M_{\text{WD},i} = 1.2 M_\odot$ and different values of $C_1$ (the “no-wind” result is also presented). Compared with Hachisu et al. (2008a), there are similar features; the allowed range of the companion star’s mass is larger for larger $C_1$. However, the parameter space in Figure 2 is somewhat smaller than in Hachisu et al. (2008a), because in Hachisu et al. (2008a) the boundaries of the SN Ia region in the $M_{2,i}$–$P_{\text{orb},i}$ plane are set by the following simplified conditions: (1) the left boundary is given by the mass–radius relation for the zero-age MS stars, (2) the lower boundary is set by the occurrence of strong nova explosions, when $\dot{M}_\text{tr} \lesssim 10^{-7} M_\odot$ yr$^{-1}$, (3) the upper boundary is set by the formation of a CE with the assumption of $\dot{M}_\text{tr} \gtrsim 10^{-4} M_\odot$ yr$^{-1}$, and (4) the right boundary corresponds to the end of central hydrogen burning of the MS companion. Additionally, Hachisu et al. (2008a) use a semi-analytical approximation to estimate the thermal-timescale mass transfer rate. In our calculations, although the mass stripping can result in a lower mass transfer rate (compared with the no-stripping case), the system still has a too-high mass transfer rate and evolves into the CE phase if the companion star’s mass $M_{2,i} \gtrsim 4–6 M_\odot$. For lower-mass companion stars considered, as calculated by Li & van den Heuvel (1997). In the latter case, the mass transfer is driven only by the nuclear evolution of the companion star. To acquire a sufficiently high mass transfer rate, the companion star should be more massive than $\sim 2 M_\odot$. When the self-excited wind from the companion star is included, the companion star’s mass can extend down to $\lesssim 1 M_\odot$. Since the wind can cause the orbit to shrink and accelerate the mass transfer, the mass transfer can maintain a rate high enough for stable burning, even if $M_2$ is not larger than $M_1$. However, this effect also lowers the upper limit of the companion’s mass and narrows the initial orbital period to some extent, because the mass transfer becomes dynamically unstable if $M_{2,i}$ or $P_{\text{orb},i}$ is larger.

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(\(M_{\text{2,i}} \lesssim 2-3 \, M_\odot\)), the mass transfer is not fast enough to drive the WD to the Chandrasekhar mass. A comparison of Figures 1 and 2 shows that the SN Ia regions in case 2 are larger than in case 1, but the lower limits of \(M_{\text{2,i}}\) are not as low as in case 1. Although both the irradiation and the wind from the WD can trigger mass loss from the companion star, their influences on the orbital evolution and hence the mass transfer are different. We find that angular momentum loss and mass loss dominate the evolution in cases 1 and 2, respectively, so that the mass transfer rates for low/high-mass companion stars are higher/lower in case 1 than in case 2. Therefore, in general, the mass-stripping effect favors more massive companion stars to drive the WDs to SN Ia explosions, while the self-excited wind is preferred for lower-mass companion stars.

Figure 3 compares the distributions of the companion mass \(M_{\text{2,i}}\) and the orbital period \(P_{\text{orb},i}\) when the WD reaches 1.38 \(M_\odot\) in cases 1 (left) and 2 (right). While the orbital periods are distributed similarly, e.g., between \(\sim 1\) day and \(\sim 12-14\) days for \(M_{\text{WD,i}} = 1.2 \, M_\odot\), the masses of the companion stars in case 1 range from \(\sim 0.3 \, M_\odot\) to \(\sim 1.8 \, M_\odot\), significantly smaller than in case 2 (\(0.3 \, M_\odot \lesssim M_{\text{WD,i}} \lesssim 4.5 \, M_\odot\)). In both cases, lower-mass companion stars are more likely to be in wider orbits because of their longer mass transfer times.

In Figures 4–6, we show the distributions of the companion’s rotating velocity versus the stellar radius, the surface gravity versus the orbital velocity, and the effective temperature versus the absolute magnitude when the WD mass reaches 1.38 \(M_\odot\) in cases 1 (left) and 2 (right), respectively. Together with Figure 3, these figures present useful probes to test the proposed SD scenarios by comparing with observational constraints (cf. Han 2008).\(^3\)

\(^3\) Note that Figures 3–6 are for the moment of the SN explosion; the realistic distributions could be changed due to the explosion. Furthermore, the donor star might evolve after the mass transfer but before the SN explosion, possibly due to the spin down of the WD to reach the critical density in its core (Justham 2011; Di Stefano et al. 2011).

4. COMPARISON WITH OBSERVATIONS

4.1. The Surviving Companions after the SNe Ia

Tycho’s Supernova (SN 1572) is close enough to search for the widowed companion to the exploded WD should it exist. Ruiz-Lapuente et al. (2004) surveyed the central region of SN 1572’s remnant and proposed that a G star appears to be the surviving companion of the SN. This star is similar to our Sun in surface temperature (\(5750 \pm 250\) K) but with a higher space velocity of \(\sim 136\) km s\(^{-1}\) and lower surface gravity (\(\sim 0.1-1.0\) km s\(^{-2}\)). These values are within the allowed regions presented in Figures 5 and 6. However, more recent observations indicate that this identification remains controversial (Fuhrmann 2005; Ihara et al. 2007; González-Hernández et al. 2009; Kerzendorf et al. 2013b).

Li et al. (2011) used the extensive historical imaging obtained at the location of SN 2011fe/PTF11kly, the closest SN Ia discovered in the digital imaging era, to constrain the visible-light luminosity of the progenitor to be 10–100 times fainter than previous limits on other SNe Ia progenitors. They proposed that the exploding WD accreted matter either from another WD or by RLOF from a subgiant or MS companion star. Edwards et al. (2012) searched for the ex-companion star in SNR 0519–69.0, located in the Large Magellanic Cloud (LMC), based on Hubble Space Telescope (HST) images with a limiting magnitude of \(V = 26.05\). They found that one of the 27 MS stars brighter than \(V = 22.7\) (corresponding to \(M_V = 4.2\)) within 4\(\prime\) of the position could be the ex-companion star left over from an SSS progenitor, ruling out SD models with post-MS stars. Kerzendorf et al. (2013a) spectroscopically scrutinized 24 of the brightest stars residing in the central 38\(''\) × 38\(''\) of the SN 1604 (Kepler) SN remnant to search for a possible surviving companion star and ruled out donor stars down to 10 \(L_\odot\). González-Hernández et al. (2012) searched for the surviving companions of the progenitor of SN 1006 and found that none of the stars within 4\(''\) of the apparent site of the explosion were associated with the SN remnant down to...
the limit of $M_V \simeq 4.9$, thus excluding all giant and subgiant companions to the progenitor. Therefore, SN 1006 should have been produced either by mass accretion from an unevolved star similar to, or less massive than, the Sun or by merging with another WD. Kerzendorf et al. (2012) also scrutinized the central stars (79 in total) of the SN 1006 remnant to search for the surviving donor star. The rotational velocities of these stars are estimated to be around 10 km s$^{-1}$. The aforementioned observational constraints on the possible surviving companions deviate significantly from what is expected based on traditional SD models, but are (in some cases barely) consistent with the results in the self-excited wind model (case 1) shown in Figures 4–6.

From the HST deep images of SNR 0509−67.5 in the LMC, Schaefer & Pagnotta (2012) reported that the maximal central error circle is empty of point sources to a limit of $V = 26.9$, which corresponds to $M_V = 8.4$. This is outside our predicted region even in the most optimistic situation. However, as
Figure 6. Distributions of the surface effective temperatures and absolute magnitudes of the companion when the WD grows to $1.38\, M_\odot$ in cases 1 (left) and 2 (right). (A color version of this figure is available in the online journal.)

discussed below, lower-mass companion stars are expected, if other effects such as the WD’s magnetic field are taken into account.

4.2. The Delay Time Distribution

Another useful feature of the SN Ia progenitors is the DTD. The DTD is the hypothetical SN rate versus time that would follow a brief burst of star formation, where the delay times are defined as the time interval between the star formation and the SN explosion. The SN Ia DTDs are directly linked to the lifetimes of the WD’s progenitor and the companion star and the binary separation. Various kinds of progenitor models of SNe Ia can be examined by comparing their DTDs with observations. Similar to the technique of Hachisu et al. (2008b), the DTD of SNe Ia from the wind-driven systems is estimated by integrating the initial sets of $(M_1, q, a)$ (where $a$ is the binary separation) with delay times between $t - \Delta t$ and $t + \Delta t$:

$$\text{DTD}(t) \propto \frac{1}{2\Delta t} \int \int \int_{t-\Delta t}^{t+\Delta t} \frac{dM_{i,j}}{M_{i,j}^{5/3}} f(q) dq d\log a. \quad (6)$$

Assuming $f(q) = 1$, we show the calculated DTDs of the two wind-driven models in Figure 7 (the SN rate has been normalized to be $10^{-3} \, \text{yr}^{-1}$). Also plotted as a solid line is the fitted form for the DTDs from current observations (Maoz & Mannucci 2012):

$$\Phi(t) = 4 \times 10^{-13} \, \text{SN yr}^{-1} \, M_\odot^{-1} \left(\frac{t}{1 \, \text{Gyr}}\right)^{-1}, \quad (7)$$

where $t$ is the delay time. Figure 7 shows that the calculated results in both cases are in agreement with Equation (7) and those in case 1 are generally longer than in case 2 because of the lower donor mass. If both models work, the DTDs can extend from a few $10^8 \, \text{yr}$ to $>12 \, \text{Gyr}$.

Figure 7. Distributions of the delay time of SNe Ia. The blue line represents the empirical power-law form (Equation (7)) for our Galaxy. (A color version of this figure is available in the online journal.)

5. DISCUSSION AND CONCLUSIONS

In the standard picture of the SD scenario for SNe Ia, a WD accretes at a rate $\gtrsim 10^{-7} \, M_\odot \, \text{yr}^{-1}$ from its companion star, which is required to power steady hydrogen burning. The fast accretion onto the WD is driven by the Roche lobe shrinking (or increasing) faster (or more slowly) than the companion star and requires a mass ratio of $>5/6$, that is, the companion stars to $1.38 \, M_\odot$ WDs must be either MS stars or (sub)giants with masses $>1.16 \, M_\odot$ (Schaefer & Pagnotta 2012). On the one hand, the companion’s mass must be $\lesssim 3-4 \, M_\odot$ to guarantee that the mass transfer is dynamically stable (Li & van den Heuvel 1997).
This value is obtained under the assumption that there are strong winds from the WD if the accretion rate is higher than the upper limit of the accretion rate for stable hydrogen burning (Hachisu et al. 1996). The properties of the surviving stars after the SN Ia explosions can thus be investigated (e.g., Han 2008).

However, observations of SNe Ia and SSSs, especially the derived DTDs of SNe Ia, the existence of 1E 0035.4—7200-like sources, and the constraints on the surviving companion stars for several nearby SNe Ia, strongly suggest that the initial masses of the companion stars should occupy a wider range than previously thought. Further revisions on the SD scenarios consider the effects of irradiation of soft X-rays from the WD on the companion star (van Teeseling & King 1998; King & van Teeseling 1998), a possible circumbinary disk around the WD binary (Chen & Li 2007), mass stripping of the companion star by the WD’s wind (Hachisu et al. 2008a), and thermal instabilities in the accretion disk (Xu & Li 2009; Wang et al. 2010).

In this paper, we calculate the evolution of WD/MS star binaries based on the self-excited wind model (van Teeseling & King 1998; King & van Teeseling 1998) and the mass-stripping model (Hachisu et al. 2008a) to produce SNe Ia. In these models, X-ray radiation or the wind from the accreting WD strongly affects the structure of the companion’s envelope, causing winds or mass loss from the donor star. This wind-driven evolution can stabilize the mass transfer when the companion is considerably more massive than the WD, thus avoiding the CE evolution, or can enhance the mass transfer rate when the companion is less massive than the WD. We have shown that the predicted properties of the companion stars are more compatible with recent observational constraints for several SNe Ia that have been investigated in detail than with the traditional SD scenario.

We caution that several issues in the wind-driven evolution models need to be addressed. It is unclear whether the self-excited wind and mass stripping work jointly or independently. The stability and efficiency of the mass transfer under these circumstances depend on the parameters \( \eta, \phi, \) and \( C_1 \), which are related to the efficiency of X-ray irradiation, the WD’s wind velocity, and the structure of the companion star; these variables are all poorly known. Furthermore, the conditions for the wind-driven evolution are not well understood, although they are theoretically permitted. For example, most of the known WD binaries with low-mass companions are ordinary cataclysmic variables (CVs) rather than SSSs, suggesting that the wind-driven case may not be popular and that some kind of accident is required to trigger the high luminosities.\(^4\) However, there are observational hints that rapid mass transfer might have occurred in CVs. For example, Zorotovic et al. (2011) show that the mean WD mass among CVs (\( M_{WD} = 0.83 \pm 0.23 \, M_\odot \)) is significantly larger than that found for pre-CVs (\( M_{WD} = 0.67 \pm 0.21 \, M_\odot \)) and single WDs (see also Warner 1973; Ritter 1985; Knigge 2006; Yuasa et al. 2010; Savoury et al. 2011). One plausible explanation is that the WD mass has grown in CVs through accretion during episodes of stable hydrogen and helium burning.

A potentially important factor we have neglected is the magnetic field of the WDs. It is well known that a considerable fraction (~25%) of CVs possess magnetic WDs named as polar and intermediate polars. Recent observations have shown that WDs with magnetic fields \( B \lesssim 3 \, \text{MG} \) have a mean mass of \( M_{WD} = 0.68 \pm 0.04 \, M_\odot \); for WDs with \( B > 3 \, \text{MG} \), \( M_{WD} = 0.83 \pm 0.04 \, M_\odot \) (Kepler et al. 2013), suggesting that mass growth may be related to the magnetic field strength.

Hydrogen burning on magnetic and non-magnetic WDs could occur in different ways, even at the same accretion rate. For accretion onto the entire surface of a WD, the accretion rate required to sustain stable hydrogen burning is ~\( 10^{-7} \, M_\odot \, \text{yr}^{-1} \). No CVs can reach such high rates driven by angular momentum loss due to magnetic braking and gravitational radiation. However, if the accreting material is funneled onto a small portion of the WD surface by the magnetic lines, then the local accretion rate will be large enough to sustain local stable hydrogen burning (Schaefer & Collazzi 2010). This enhances the effective rate of the accretion compared with spherical accretion. The fraction of the WD surface covered by the accretion spot measured in magnetic CV systems is typically ~\( 10^{-3} - 10^{-2} \) (Schaefer & Collazzi 2010, and references therein), thus steady hydrogen burning requires that the accretion rate be \( \gtrsim 10^{-10} - 10^{-9} \, M_\odot \, \text{yr}^{-1} \). This means that magnetic WDs may achieve a long-lasting SSS phase with a significantly lower accretion rate than non-magnetic WDs. X-ray irradiation from the SSS will be able to heat the surface of the companion star, excite winds, and sustain a relatively high accretion rate for a long time. This configuration was recently discussed by Wheeler (2012) in the context of WD/M dwarf binaries. Wheeler argues that even modest magnetic fields on the WDs and M dwarfs would be able to lock the two stars together, resulting in a slowly rotating WD. The mass loss would be channeled by a magnetic bottle connecting the two stars, landing on a concentrated polar area on the WD. Luminosity from the accretion and hydrogen burning on the surface of the WD may induce self-excited mass transfer. Obviously, the wind-driven evolution of magnetic WDs is of great interest as a possible pathway to SNe Ia and should be investigated in future work.

This work was supported by the Natural Science Foundation of China under grant numbers 11133001 and 11333004, the National Basic Research Program of China (973 Program 2009CB824800), and the Qinglan project of Jiangsu Province.

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\(^4\) One possible way is a long phase of residual hydrogen burning after a mild shell flash or a late helium shell flash of the cooling WD after the system has already come into contact as a CV (King & van Teeseling 1998).
