WD+MS Systems as Progenitors of Type Ia Supernovae with Different Metallicities

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Abstract

The single-degenerate model for the progenitors of type Ia supernovae (SNe Ia) is one of the two most popular models, in which a carbon–oxygen white dwarf accretes hydrogen-rich material from its companion, increases its mass to the Chandrasekhar mass limit, and then explodes as a SN Ia. Incorporating the prescription of Hachisu et al. (1999a, ApJ, 519, 314) for the accretion efficiency into Eggleton’s stellar evolution code and assuming that the prescription is valid for all metallicities, we carried out a detailed binary evolution study with different metallicities. We showed the initial and final parameter space for SNe Ia in a (log $P$–$M_2$) plane. The positions of some famous recurrent novae in the (log $P$–$M_2$) plane, as well as a supersoft X-ray source (SSS), RX J0513.9−6951 are well explained by our model, and our model can also explain the space velocity and mass of Tycho G, which is now suggested to be a companion star of Tycho’s supernova. Our study indicates that a SSS, V Sge, is a potential progenitor of supernovae, like SN 2002ic, if the delayed dynamical-instability model in Han and Podsiadlowski (2006, MNRAS, 368, 1095) is appropriate.

Key words: stars: binaries: general — stars: individual (SN 2002ic) — stars: supernovae: general — stars: white dwarfs

1. Introduction

Type Ia supernovae (SNe Ia) play an important role as cosmological distance indicators, and have been successfully applied to determine cosmological parameters (e.g., $\Omega$ and $\Lambda$: Riess et al. 1998; Perlmutter et al. 1999), which have led to the discovery of the accelerating expansion of the universe. However, the exact nature of SNe Ia progenitors has not been clarified (see the reviews by Hillebrandt & Niemeyer 2000; Leibundgut 2000). It is generally agreed that SNe Ia originate from a thermonuclear runaway of a carbon–oxygen white dwarf (CO WD) in a binary system. The CO WD accretes with material from its companion, increases mass to its maximum stable mass, and then explodes as a thermonuclear runaway. Almost half of the WD mass is converted into radioactive nickel-56 in the explosion (Branch 2004), and the amount of nickel-56 determines the maximum luminosity of SNe Ia (Arnett 1982).

According to the nature of the companions of mass-accreting white dwarfs, two competing scenarios have been proposed, i.e., a double-degenerate channel (DD: Iben & Tutukov 1984; Webbink & Iben 1987) and a single degenerate channel (SD: Whelan & Iben 1973; Nomoto et al. 1984). In the DD channel, two CO WDs with a total mass larger than the Chandrasekhar mass limit may coalesce, and then explode as a SN Ia. Although the DD channel is theoretically less favored, e.g., double WD mergers are more likely to result in accretion-induced collapses rather than SNe Ia (Hillebrandt & Niemeyer 2000), it is premature to exclude the channel at present, since there exists evidence that the channel may contribute to a few SN Ia (Howell et al. 2006; Branch 2006; Quimby et al. 2007). The single-degenerate Chandrasekhar model is an alternative of DD and some surveys have shown that many SD systems are being good candidates for SNe Ia (Whelan & Iben 1973; Nomoto et al. 1984; Parthasarathy et al. 2007). In this model, the maximum stable mass of a CO WD is $\approx 1.378 \, M_\odot$ (close to the Chandrasekhar mass, Nomoto et al. 1984), and the companion is probably a main-sequence star, or a slightly evolved star (WD+MS) or a red-giant star (WD+RG) (Yungelson et al. 1995; Li & van den Heuvel 1997; Hachisu et al. 1999a, 1999b; Nomoto et al. 1999; Langer et al. 2000; Han & Podsiadlowski 2004; Meng et al. 2009a). The SD model is supported by many observations. For example, variable circumstellar absorption lines were observed in the spectra of SN Ia 2006X (Patat et al. 2007), which indicates the SD nature of its precursor. Patat et al. (2007) suggested that the progenitor of SN 2006X is a WD+RG system based on the expansion velocity of the circumstellar material, while Hachisu et al. (2008) argued for a WD+MS nature for this SN Ia. Recently, Voss and Nelemans (2008) suggested that SN 2007on is also possible from a WD+MS channel. In this paper, we only focus on the WD+MS channel, which is a very important channel for producing SNe Ia in our Galaxy (Han & Podsiadlowski 2004).

Observationally, some WD+MS systems are possible progenitors of SNe Ia (see the review of Parthasarathy et al. 2007). For example, supersoft X-ray sources (SSSs) were suggested as being good candidates for the progenitors of
SNe Ia (Hachisu & Kato 2003b, 2003c). Some of the SSSs are WD+MS systems and some are WD+RG systems (Di Stefano & Kong 2003). Di Stefano and Kong (2003) reported that in every galaxy there are at least several hundred SSSs with a luminosity of $\geq 10^{37}$ erg s$^{-1}$ based on Chandra data from four external galaxies (an elliptical galaxy, NGC 4967; two face-on spiral galaxies, M 101 and M 83; and an interacting galaxy, M 51). They also noticed that the SSSs appear to be associated with the spiral arms in the spiral galaxies, which may indicate that SSSs are young systems (WD+MS systems?). Recurrent novae may also be good candidates as the progenitors of SNe Ia (Branch et al. 1995), and several novae have been suggested to be possible progenitors (Hachisu et al. 2000a, 2000b; Hachisu & Kato 2000, 2003a, 2005, 2006a, 2006b; Hachisu et al. 2007). Some of the novae are WD+MS systems and some are WD+RG systems.

A direct way to confirm the progenitor model is to search for companion stars of SNe Ia in their remnants. The discovery of a potential companion of Tycho’s supernova has verified the power of the method, and also the reliability of the WD+MS model (Tycho G named in Ruiz-Lapuente et al. 2004). Recently, González Hernández et al. (2009) verified the power of the method, and also the reliability of the MS model (Tycho G named in Ruiz-Lapuente et al. 2004). Recently, González Hernández et al. (2009) verified the power of the method, and also the reliability of the MS model (Tycho G named in Ruiz-Lapuente et al. 2004). Recently, González Hernández et al. (2009) verified the power of the method, and also the reliability of the MS model (Tycho G named in Ruiz-Lapuente et al. 2004). Recently, González Hernández et al. (2009)

Many studies have concentrated on the WD+MS channel. Some authors (Hachisu et al. 1999a, 1999b, 2008; Nomoto et al. 1999, 2003) have studied the WD+MS channel by a simple analytical method to treat binary interactions. Such analytic prescriptions may not describe some mass-transfer phases, especially those occurring on a thermal time-scale (Langer et al. 2000.). Li and van den Heuvel (1997) studied this channel from a detailed binary evolution calculation, while they considered two WD masses (1.0 and 1.2 $M_\odot$). Langer et al. (2000) investigated the channel for metallicities $Z = 0.001$ and 0.02, but they only studied the case A evolution (mass transfer during core hydrogen burning phase). Han and Podsiadlowski (2004) carried out a detailed study of this channel including case A and early case B (mass transfer occurs at Hertzsprung gap, HG) for $Z = 0.02$. Following the study of Han and Podsiadlowski (2004), Meng, Chen, and Han (2009a) studied the WD+MS channel comprehensively and systematically at various $Z$, and showed the initial parameter spaces for the progenitors of SNe Ia and the distributions of the initial parameters for the progenitors of SNe Ia. Here, based on a study in Meng, Chen, and Han (2009a), we want to show the final parameter spaces of companions at the moment of SNe Ia explosion, and check whether the model used in Meng, Chen, and Han (2009a) can explain the properties of some recurrent novae and SSSs, which are suggested to be the possible progenitors of SNe Ia, and the properties of Tycho G, which is a potential companion of Tycho’s supernova.

In section 2, we simply describe the numerical code for binary evolution calculations. The evolutionary results are shown in section 3. In section 4, we briefly discuss our results, and finally we summarize the main results in section 5.

2. Binary Evolution Calculation

Our method for treating the binary evolution of WD+MS systems is the same as that in Meng, Chen, and Han (2009a). In the following, we simply rederive our method. We use the stellar evolution code of Eggleton (1971, 1972, 1973) to calculate the binary evolutions of WD+MS systems. The code has been updated with the latest input physics over the last three decades (Han et al. 1994; Pols et al. 1995, 1998). Roche lobe overflow (RLOF) was treated within the code described by Han, Tout, and Eggleton (2000). We set the ratio of mixing length to local pressure scale height, $\alpha = l/H_p$, to 2.0, and set the convective overshooting parameter, $\delta V$, to 0.12 (Pols et al. 1997; Schröder et al. 1997), which roughly corresponds to an overshooting length of 0.25 $H_p$. Ten metallicities were adopted here (i.e., $Z = 0.0001, 0.0003, 0.001, 0.004, 0.01, 0.02, 0.03, 0.04, 0.05, and 0.06$). The opacity tables for these metallicities were compiled by Chen and Tout (2007) from Iglesias and Rogers (1996) and Alexander and Ferguson (1994). For each $Z$, the initial hydrogen mass fraction is obtained from

$$X = 0.76 - 3.0 Z,$$

since this relation can well reproduce the color–magnitude diagram (CMD) of some clusters (Pols et al. 1998). Instead of solving stellar structure equations of a WD, we adopted the prescription of Hachisu et al. (1999a) on WDs accreting hydrogen-rich material from their companions. In a WD+MS system, the companion fills its Roche lobe at MS or during HG, and transfers material onto the WD. We assumed that if the mass-transfer rate, $|\dot{M}|$, exceeds a critical value, $\dot{M}_{cr}$, the accreted hydrogen-rich material steadily burns on the surface of WD, and is converted into helium at the rate of $M_{He}$. The unprocessed matter is lost from the system as an optically thick wind at a rate of $\dot{M}_{wind} = |\dot{M}| - \dot{M}_{cr}$ (Hachisu et al. 1996). Based on the opacity from Iglesias and Rogers (1996), the optically thick wind is very sensitive to Fe abundance, and it is possible for the wind not to work when $Z < 0.002$ (Kobayashi et al. 1998). Thus, there should be an obvious low-metallicity threshold for SNe Ia in comparison with SN II. However, this metallicity threshold was not found (Prieto et al. 2008). Considering the uncertainties in the opacities, we therefore assumed rather arbitrarily that the optically thick wind is valid for all metallicities.

The critical accretion rate is given by

$$\dot{M}_{cr} = 5.3 \times 10^{-5} \frac{(1.7 - X)}{X} (M_{WD} - 0.4),$$

where $M_{WD}$ is the mass of the accreting WD (mass is in $M_\odot$) and mass-accretion rate is in $M_\odot$ yr$^{-1}$, Hachisu et al. 1999a). The effect of metallicities on equation (2) has not been included, since its effect is very small and can be neglected (Meng et al. 2006).

We adopted the following assumptions when $|\dot{M}| \leq \dot{M}_{cr}$:

1. When $|\dot{M}| \geq \frac{1}{2} \dot{M}_{cr}$, the hydrogen-shell burning is steady and no mass is lost from the system.
2. When $\frac{1}{2} \dot{M}_{cr} > |\dot{M}| \geq \frac{1}{8} \dot{M}_{cr}$, a very weak shell flash is triggered, but no mass is lost from the system.
3. When $|\dot{M}| < \frac{1}{8} \dot{M}_{cr}$, the hydrogen-shell flash is so strong that no material can be accumulated by the accreting CO WD. Then, the growth rate of the mass
of the helium layer under the hydrogen-burning shell can be defined as

\[ \dot{M}_{\text{He}} = \eta_H |\dot{M}_2|, \]  

where \( \eta_H \) is the mass accumulation efficiency for hydrogen burning; its values is

\[ \eta_H = \begin{cases} \dot{M}_{\text{cr}} / |\dot{M}_2|, & |\dot{M}_2| > \dot{M}_{\text{cr}}, \\ 1, & \dot{M}_{\text{cr}} \geq |\dot{M}_2| \geq \frac{1}{8} \dot{M}_{\text{cr}}, \\ 0, & |\dot{M}_2| < \frac{1}{8} \dot{M}_{\text{cr}}. \end{cases} \]  

When a certain amount of helium is accumulated, helium is ignited as a He-flash, and some of the helium is blown off from the surface of the CO WD. Then, the mass growth rate of the CO WD, \( \dot{M}_{\text{WD}} \), is

\[ \dot{M}_{\text{WD}} = \eta_{\text{He}} \dot{M}_{\text{He}} = \eta_{\text{He}} \eta_H |\dot{M}_2|, \]  

where \( \eta_{\text{He}} \) is the mass accumulation efficiency for helium-shell flashes, and its value is taken from Kato and Hachisu (2004).

We assume that if an accreting CO WD increases its mass to 1.378 \( M_\odot \) (Nomoto et al. 1984), it explodes as a SN Ia.

3. Results

3.1. Final State of Binary Evolution

In figure 1, we show the initial contour for SNe Ia and the final state of binary evolution in \((\log P - M_2)\) plane at the moment of SNe Ia explosion for the case of \( \dot{M}_{\text{WD}}^i = 1.1 \ M_\odot \) with \( Z = 0.02 \). The accreting WD may reach a mass of 1.378 \( M_\odot \) during the optically thick wind phase (the filled squares, Case Wind), or after optically thick wind while in a stable (the filled circles, Case Calm) or unstable (the filled triangles, Case Nova) hydrogen-burning phase. At the first glance, the position of the final contour is much lower than that of the initial contour, which results from mass transfer.
from secondary to white dwarf and mass loss from the system. A SSS, RX J0513.9-6951 (open star), whose WD mass is $1.30 M_\odot$ (Hachisu & Kato 2003b), locates in the initial contour. It should be a good candidate for the progenitor of SN Ia, as suggested in Hachisu and Kato (2001) and Hachisu and Kato (2003b). Three recurrent novae (U Sco, V394 CrA, and CI Aql) are outside the initial contour for SNe Ia, while still inside the final region. The WD mass of U Sco was estimated to be $1.37 M_\odot$ (Hachisu et al. 2000a, 2000b), which is very close to $1.378 M_\odot$. The MS mass of U Sco is $1.5 M_\odot$ (Hachisu et al. 2000a, 2000b), which still has enough material to transfer onto the WD and increases the WD mass to $1.378 M_\odot$. Thus, U Sco is a very likely candidate for the progenitor of SN Ia (see also Hachisu et al. 2000a, 2000b).

The WD masses of V394 CrA and CI Aql were estimated to be $1.37 M_\odot$ and $1.2 M_\odot$, respectively. Their companion masses are still unclear. The best-fit companion masses for the two recurrent novae are $1.50 M_\odot$, while $1.0 M_\odot$–$2.0 M_\odot$ is still accepted (Hachisu & Kato 2000, 2003a; Hachisu et al. 2003). Thus, based on our binary evolution calculation, V394 CrA is a very likely progenitor of SN Ia and CI Aql is a possible progenitor of SN Ia. A further observation to confirm their companion masses is necessary for judging their fates. Another very famous recurrent nova is V1974 Cyg (Novák Cygni 1992), whose companion mass is $0.21 M_\odot$ (DeYoung & Schmidt 1994; Retter et al. 1997), and the orbital period is 0.0813 days (Paresce et al. 1995; Retter et al. 1997). Its position is outside the final contour in this paper. Considering its low WD mass ($1.0 M_\odot$–$1.1 M_\odot$, Hachisu & Kato 2005), it is very unlikely for V1974 Cyg to become a SN Ia (see Hachisu et al. 2008 for similar discussions about these recurrent novae).

In figure 2, we present the initial contours for SNe Ia and the final state in the $(\log P - M_2)$ plane at the moment of SNe Ia explosion for different initial WD masses with $Z = 0.02$. This figure further confirms the likelihood for V394 CrA and CI Aql to be the progenitors of SNe Ia.

In figure 3, we show the trend of the initial and final contours with metallicity. For clarity, we only show the case of $M_\text{WD} = 1.10 M_\odot$, since the other cases give similar results (see figure 4 in Meng et al. 2009a). We can see from the figure that there is a clear trend for the initial and final contours to move to higher masses with metallicity. This is due to the correlation between the stellar evolution and metallicity. Generally, stars with high metallicity evolve in a way similar to those with low metallicity, but less mass (Umeda et al. 1999; Chen & Tout 2007; Meng et al. 2008). Thus, for binaries of CO WDs with particular orbital periods, the companion mass increases with the metallicity (see Meng et al. 2009a in details).

### 3.2 Case Wind

We present the initial and final states of binary evolution of SNe Ia for Case Wind in figures 4 and 5. Figure 4 is only for the case of $M_\text{WD} = 1.10 M_\odot$, since the other cases give similar results (see figure 3). In these two figures, we can see that the range of the initial MS masses with $Z = 0.02$ for the Case Wind is between $2.2 M_\odot$ and $3.5 M_\odot$. However, the range strongly depends on the metallicity; that is, the progenitor systems have more massive companions for a higher $Z$ (see figure 3 in this paper).
Fig. 5. Similar to figure 4, but for different initial WD mass. Different colors represent different initial WD masses. The big filled squares show the initial WD+MS systems, while the small ones show their final positions at the moment of SNe Ia explosion. In the figure, we do not plot the cases with \( M_i < 0.9 M_\odot \) for the clarity of appearance of the figure since no Case Wind occurs for the cases.

and figure 4 in Meng et al. 2009a). Hachisu et al. (2008) found that when \( M_{i,WD} \leq 0.9 M_\odot \), no Case Wind exists for \( Z = 0.02 \). We obtain a similar results for \( Z = 0.02 \). However, this result also depends on the metallicity. For example, the mass limit for no wind is \( 0.8 M_\odot \) for \( Z = 0.06 \), while it is larger than \( 1.0 M_\odot \) for \( Z = 0.0001 \). In addition, Hachisu et al. (2008) noticed that only when \( M_2 \geq 3.0 M_\odot \), WDs explode at the optically thick wind phase as SNe Ia. Their result is very different from that in this paper. The difference is derived from the different treatment on mass transfer between WD and MS and from a different mass-loss mechanism from the system. Firstly, they used an analytic method for treating a binary interaction. This method can not describe a certain mass-transfer phase, particularly those occurring on a thermal time-scale, and may overestimate the mass-transfer phase on the thermal time-scale (Langer et al. 2000; see also the figures 1 and 4 in Han & Podsiadlowski 2004). Secondly, they assumed a mass-stripping effect; that is, optically thick winds from WD collide with secondary and strip off its surface layer. This effect may attenuate the mass-transfer rate between the WD and its companion, but the total mass-loss rate from the secondary increases (Hachisu & Kato 2003a, 2003b; Hachisu et al. 2008). For the two reasons mentioned above, more materials are thus lost from binary systems as the optically thick wind and stripped-off material before a supernova explosion, and then the systems are more likely to explode after an optically thick wind.

The material lost as the optically thick wind forms a circumstellar material (CSM), which may result in a color excess of SNe Ia (Meng et al. 2009b). Since the CSM is very close to SN Ia for Case Wind, the ejecta of an explosion may interact with the CSM, and the SN Ia might then be observed as a supernova, like SN 2006X, which show a variable Na I D line (Patat et al. 2007; Blondin et al. 2009). We will discuss this in a future paper.

In the final contours, there is no special region for Case Wind (see figure 5); that is, WDs can explode as SNe Ia at any position in the final permitted region in the \( \log P-M_2 \) plane, which is very different from the Case Calm and the Case Nova (see the following subsection).

3.3. Case Calm

If the mass-transfer rate from the secondary onto WD is below the critical accretion rate [equation (2)], while above the lowest rate of steady hydrogen burning before a supernova explosion, i.e., \( \dot{M}_{cr} \geq |M_2| \geq \frac{1}{2} \dot{M}_{cr} \), the WD undergoes steady H burning at the moment of the SN Ia explosion. This is the reason why we call this “Case Calm” (same as that in Hachisu et al. 2008). During the steady hydrogen-burning phase, the WD may be observed as a SSS. The material lost as an optically thick wind forms CSM, but it has been dispersed and become too washy to be detected immediately after the SN Ia explosion. In figures 6 and 7, we show the initial and final states of the binary evolution of SNe Ia for...
Case Calm in the \((\log P - M_2)\) plane. Figure 6 is only for the case of \(M_{\text{WD}}^{i} = 1.1M_\odot\), and figure 7 is for different initial WD masses. Here, we only show the case of \(Z = 0.02\) as a typifier, since the other cases give similar results (also see figure 3). In figure 6, it is clear that there is a gap for both the initial system and the final state in the \((\log P - M_2)\) plane, and the gap divides Case Calm into two groups. The gap in the initial contour is the region for Case Wind, and the area of the gap decreases with \(M_{\text{WD}}^{i}\) decreasing. When \(M_{\text{WD}}^{i} < 0.9M_\odot\), the gap disappears (see figure 7).

The gap is also shown in the initial \((\log P - M_2)\) plane of Han and Podsiadlowski (2004) and Meng, Chen, and Han (2009a), but they did not discuss it. In this paper, we explain its origin as follows. For the high-mass group in the initial contour of figure 6, their mass ratio is large. After the onset of Roche lobe overflow (RLOV), the mass-transfer rate is so high that the system almost becomes dynamically unstable. At this stage, a large amount of hydrogen-rich materials become lost as the optically thick wind, and hence the secondary mass decreases sharply. The mass-transfer rate drops after the mass ratio has been reversed, and then the optically thick wind stops. When CO WD mass increases to \(1.378M_\odot\), the secondary mass decreases to about \(0.9M_\odot\), which corresponds to the low-mass group in the final-state contour of figure 6.

For the low-mass group in the initial contour of figure 6, their mass ratio is not very large, and only a small amount of hydrogen-rich materials is lost as the optically thick wind, which means that most of the transferred materials are accumulated on the WD. Then, the secondary mass decreases slightly, which forms a high-mass group in the final-state contour of figure 6.

In figure 7, there is a blank region in the final-state region for Case Calm (around \(M_{\text{SN}}^{2} = 1.4M_\odot - \log P = 0.6\)), which means that SSSs may not be observed in this region before the SNe Ia explosion. This phenomena is much different from that of Case Wind. The blank region is mainly derived from the low-mass group in the initial contour. For a system belonging to the group, mass transfer is almost conservative, and then the period is always decreasing, since the mass ratio is not reversed, which leads to the region absenting long-period systems. For a system in the high-mass, although its period decreases during the optically thick wind, the period increases after a mass-ratio reversion, since no material loses from the system and the mass transfer becomes conservative [see the panel (h) of figure 1 in Han & Podsiadlowski 2004]. Thus, its final period is a bit complicated.

### 3.4. Case Nova

If the mass-transfer rate from secondary onto WD is below the lowest rate of steady hydrogen burning, while still higher than a special value, i.e., \(\frac{1}{2}M_{\text{cr}} > |M_2| \geq \frac{1}{8}M_{\text{cr}}\), hydrogen shell burning is unstable to flash, and this can recur many times in a short period as a recurrent nova. We call this “Case Nova” (similar to Hachisu et al. 2008). During the last recurrent nova phase, the amount of the hydrogen-rich material lost from the system is very small. On the other hand, the material lost as the optically thick wind is already very far from the center of the SN Ia explosion. It will take 100–1000 yr for the SN Ia ejecta to catch material lost as the optically thick wind (Hachisu et al. 2008), and thus no signal with information about CSM can be detected immediately after the supernova explosion. In figures 8 and 9, we show the initial and final states of the binary evolution of SNe Ia for Case Nova in the \((\log P - M_2)\) plane. Figure 8 is only for the case of \(M_{\text{WD}}^{i} = 1.1M_\odot\) and figure 9 is for different initial WD masses. Here, we only show the case of \(Z = 0.02\) as a prototype, since the other cases give similar results (also see figure 3). The initial region of Case Nova is also divided into two group, which is similar to that of Case Calm. The systems located in the gap are those for Case Wind or Case Calm. The difference between Case Calm and Case Nova is that the gap disappears when \(M_{\text{WD}}^{i} = 0.8M_\odot\), not \(0.9M_\odot\) (see figure 9). For a similar reason to that of Case Calm, the high-mass group in the initial contour forms a low-mass group in the final contour, while the low-mass group in the initial contour forms a high-mass group in the final contour.
Similar to figure 7, there is also a blank region in figure 9 (around $M_{SN}^2 = 1.3 M_\odot - \log P = 0.5$). The origin of the blank region is similar to that of Case Calm.

The recurrent nova U Sco, which is an excellent candidate of the SN Ia progenitor (Hachisu et al. 2000a, 2000b), is located in the middle of the final region, and its position in the $(\log P - M_2)$ plane is just the permitted region for a recurrent nova (see figure 9). Our model can explain the position of U Sco excellently.

3.5. Companion State after a SNe Ia Explosion

A good way to discriminate between the many SN Ia progenitor scenarios is to search for 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 the explosion), it survives, and shows some special properties in its spectra, which is originated from contamination of the supernova ejecta (Marietta et al. 2000; Ruiz-Lapuente et al. 2004; Branch 2004). Tycho’s supernova, which is one of only two SN Ia observed in our Galaxy, provides an opportunity to address observationally 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. However, Ihara 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; an analysis of the chemical abundances of Tycho G upholds the companion nature of the Tycho G (González Hernández et al. 2009).

However, 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 the companion and strips some hydrogen-rich material from its surface. After the collision, the companion gains a kick velocity, which is much smaller than the orbital velocity, and leaves the explosion center at a velocity similar to its orbital velocity (Marietta et al. 2000; Meng et al. 2007).

For a companion star in the remnant of a SN Ia, its mass and space velocity can be detected directly. Since the stripped-off hydrogen-rich material from companion surface and the change of the space velocity of companion resulting from the collision of explosion ejecta are both small (Marietta et al. 2000; Mattila et al. 2005; Leonard 2007; Meng et al. 2007), we can approximately use the state of a companion at the moment of a supernova explosion to present its final state after a supernova explosion. In figure 10, the final states of companion stars are presented in the $V_{\text{orb}}$–$M_{SN}^2$ (orbital velocity–final companion mass) plane for different initial WD masses with $Z = 0.02$. From the figure, we can see that the range of the space velocity is from 70 km s$^{-1}$ to 210 km s$^{-1}$, and the mass is between 0.6 $M_\odot$ and 2.5 $M_\odot$. Tycho G is just located in this range. Our work can explain the observation. In a future paper, we will give detailed results about Tycho G by using the approach of binary population synthesis.

The effect of metallicity on the final state of the companions is shown in figure 11. In this figure, we only show the case of $M_{WD} = 1.10 M_\odot$, since the other cases give similar results. We can see from the figure that all of the metallicity may explain the properties of Tycho G. However for a detailed binary population synthesis study, only the case of $Z = 0.02$ can well explain the position of Tycho G in the $V_{\text{orb}}$–$M_{SN}^2$ plane. Please notice our future paper.

4. Discussion

4.1. Initial and Final Contours

In this paper, we show the initial and final parameter spaces for the SNe Ia in $(\log P - M_2)$ plane. The final masses of the companions are between 0.6 $M_\odot$ and 2.5 $M_\odot$ for $Z = 0.02$. However, the range of the companion masses in Hachisu et al. (2008) is from 1.2 $M_\odot$ to about 3 $M_\odot$. This difference is directly derived from the different initial contours, which is mainly determined by the different treatment of the thermal timescale mass transfer and different mass-loss mechanism. They used a simply analytic method to estimate the mass-transfer rate, which led to a different initial contour for
SNe Ia, especially for low-mass WD (Han & Podsiadlowski 2004). In addition, they assumed a mass-stripping effect, and thus, the initial companion mass may be as large as \(8 M_\odot\), which depends on the efficiency of the mass-stripping effect. Since their final mass of the companion is always larger than \(1.2 M_\odot\), it is difficult for their model to explain the properties of Tycho G, which remains consistent with the surviving companion of Tycho’s supernova (1 \(M_\odot\); Ruiz-Lapuente et al. 2004; González Hernández et al. 2009). Since our results are based on a detailed binary evolution calculation with the latest input physics, our results are more realistic, and the final contours in this paper are more likely to approach the real ones than those in Hachisu et al. (2008) (see also in Han & Podsialdowski 2004). Because of the difference range of the final companion as mentioned above, Tycho G can be a likely progenitor of Tycho’s supernova in our model, but can not be in the model of Hachisu et al. (2008).

4.2. Supernovae like SN 2002ic and V Sge

Until SN 2002ic was discovered (Hamuy et al. 2003), it was long believed that there are no hydrogen lines in the spectra of SNe Ia. The strong hydrogen lines in the spectra of SN 2002ic were explained by the interaction between the SN ejecta and the circumstellar material (CSM) (Hamuy et al. 2003). Recently, two co-twins of SN 2002ic (SN 2005gj and SN 2006gy) were also found (Aldering et al. 2006; Ofek et al. 2007). To explain these rare objects, many models were suggested, and here we just list some of them: Hachisu et al. (1999b); Hamuy et al. (2003); Livio and Riess (2003); Chugai and Yungelson (2004); Han and Podsialdowski (2006); Hachisu et al. (2008); Lü et al. (2009). Among all of the models listed above, the delayed dynamical instability model suggested by Han and Podsialdowski (2006) is more interesting, and some predictions from the model seem to be consistent with observations, especially in a sense of the birth rate and delay time of these rare objects (Aldering et al. 2006; Prieto et al. 2007). In the scenario of Han and Podsialdowski (2006), SN 2002ic might be from the WD+MS channel, where the CO WD accretes to material from its relatively massive companion (\(\sim 3.0 M_\odot\)), and increases its mass to \(\sim 1.30 M_\odot\) before experiencing a delayed dynamical instability. Adopting their model, Meng, Chen, and Han (2009a) assumed that the CO WD can increase its mass to \(1.378 M_\odot\), and explode as a SN 2002ic-like case if the mass of the CO WD exceeds \(1.30 M_\odot\) before the delayed dynamical instability. They then predicted that supernovae like SN 2002ic may not be found in extremely low-metallicity environments. Under the same assumption as that of Meng, Chen, and Han (2009a), we show the permitted region for the delayed dynamical instability model with various metallicities in figure 12. For simplicity of the assumption, the real region for the delayed dynamical instability model may be larger than that shown in figure 12 (see figure 5 in Han & Podsialdowski 2006 and figure 2 in Meng et al. 2009a). It is clear that the permitted region for supernova like SN 2002ic lies above the contours for normal supernova. There is an overlap between supernova like SN 2002ic and normal SN Ia, since a progenitor of supernova like SN 2002ic with low metallicity may have a lower mass than that of normal supernovae. Whatever, more evidence is necessary to confirm the scenario in Han and Podsialdowski (2006), especially to find a progenitor system at present.

V Sge is a well-observed quasi-periodic transient SSS in our Galaxy. It switches the optical state between a high (\(V \sim 11\) mag) and low (\(V \sim 12\) mag) states; during the low state, very soft and very weak X-rays can be detected (Greiner & van Teeseling 1998). The mass-loss rate for V Sge can be as large as \(\sim 10^{-5} M_\odot\) yr\(^{-1}\) indicated by radio observations (Lockley et al. 1997, 1999). Hachisu and Kato (2003c) used an optically thick wind to explain the observational property of V Sge excellently, and in their model the mass-loss rate may reach as high as \(\sim 10^{-2} M_\odot\) yr\(^{-1}\), which is consistent with radio observations. Hachisu and Kato (2003c) also estimated the WD mass as being \(M_{\text{WD}} \sim 1.25 M_\odot\); its companion mass as \(M_2 \sim 3.5 M_\odot\); and they then suggested that V Sge will explode as a SN Ia after about 10\(^5\) yr. However, they must assume a mass-stripping effect, or otherwise the position of the V Sge in (\(\log P – M_2\)) plane will be beyond the permitted region for stable mass transfer (Hachisu et al. 2008). We obtained a similar result to that in Hachisu et al. (2008), that V Sge is located in a forbidden zone for stable mass transfer if there is no special assumption (see in figure 12). However, it lies at the boundary of the contour for supernovae like SN 2002ic, as indicated in Han and Podsialdowski (2006). Considering the smaller region here than a real one and a moderately larger WD mass of V Sge than that in this paper, V Sge is a potential progenitor system that will undergo a delayed dynamical instability, as suggested in Han and Podsialdowski (2006). V Sge thus would not explode as a normal SN Ia, but one like SN 2002ic, if the model in Han and Podsialdowski (2006) is appropriate. Then, we might regard “V Sge-type stars” as being a progenitor of supernova like SN 2002ic, if it belongs to the WD+MS system.

The lifetime of a V Sge-type star is typically \(\sim 10^5\) yr, which is mainly due to the time-averaged wind mass-loss rate of...
\[ \sim 10^{-5} M_\odot \text{yr}^{-1} \] (Han & Podsia\l{}owski 2006). Since no more than 1 in 100 SNe Ia belong to the subgroup of 2002ic-like supernovae (Han & Podsia\l{}owski 2006; Aldering et al. 2006; Prieto et al. 2007), there should be several V Sge-type stars belonging to the WD+MS system in our Galaxy if we take the galactic birth rate of SNe Ia as \( 3-4 \times 10^{-3} \text{yr}^{-1} \) (van den Bergh & Tammann 1991; Cappellaro & Turatto 1997). Steiner and Diaz (1998) listed four V Sge-type stars in the Galaxy, and discussed their similar spectroscopic and photometric properties. At present, their companion masses have not been identified, while their orbital periods are in the range of 0.2–0.5 days, which falls into the orbital periods predicted by our model (see the final regions in figure 3). Please notice that not all SSSs belong to WD+MS systems, and the nature of the compact star still remains an open question (Steiner & Diaz 1998). White dwarfs, neutron stars, black holes, or even carbon main-sequence stars are all possible candidates (Steiner & Diaz 1998). Another alternative for the SSSs is the WD+He star system, which may also contribute to a few parts of SNe Ia (Wang et al. 2009). Thus, considering the uncertainty in the nature of the four V Sge-type stars, our estimation on the number of V Sge-type stars is consistent with observations.

However, although the life, mass-loss rate, and the number of V Sge-type stars seem to match with the prediction from the delayed dynamical instability model, the case of \( M_1 = 1.2 M_\odot \) is the only one in our model grids to account for the position of V Sge in the \((\log P - M_2)\) plane, while there exist arguments on whether the mass of a CO WD may be as large as \( 1.2 M_\odot \) and whether the CO WD of \( 1.2 M_\odot \) may explode as a SN Ia (Umeda et al. 1999; Meng et al. 2008). Thus, obtaining a conclusion on whether there is a relation between a V Sge-type star and the delayed dynamical instability model is premature, and V Sge is only a potential candidate for the progenitor of supernovae like SN 2002ic.

5. Summary and Conclusions

Adopting the prescription in Hachisu et al. (1999a) for the mass accretion of CO WDs, we carried out detailed binary evolution calculations for the progenitors of SNe Ia with different metallicity in the single-degenerate channel (the WD+MS channel), and obtained the initial and final parameters in the \((\log P - M_2)\) plane. Our model may explain the positions of some famous recurrent novae in the \((\log P - M_2)\) plane, as well as a SSS, RX J0513.9–6951. Our model can also explain the space velocity and mass of Tycho G, which is now suggested to be a potential companion star of Tycho’s supernova (Ruiz-Lapuente et al. 2004; González Hernández et al. 2009). Based on the delayed dynamically unstable model in Han and Podsia\l{}owski (2006), we might regard V Sge as being a potential progenitor of supernova like SN 2002ic.

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