YOUNG AND MASSIVE BINARY PROGENITORS OF TYPE Ia SUPERNOVAE AND THEIR CIRCUMSTELLAR MATTER
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ABSTRACT
We present new evolutionary models for Type Ia supernova (SN Ia) progenitors, introducing the mass-stripping effect on a main-sequence (MS) or slightly evolved companion star by winds from a mass-accreting white dwarf (WD). The mass stripping attenuates the rate of mass transfer from the companion to the WD. As a result, a very massive MS companion can avoid forming a common envelope and thus can increase the WD mass up until the SN Ia explosion. Including the mass-stripping effect, we follow binary evolutions of various WD + MS systems and obtain the parameter region in the initial donor mass–orbital period plane in which SNe Ia occur. The newly obtained SN Ia region extends to donor masses of 6–7\(M_\odot\), although its extension depends on the efficiency of the mass-stripping effect. The stripped matter would mainly be distributed on the orbital plane and would form very massive circumstellar matter (CSM) around the SN Ia progenitor. This can explain the massive CSM around the Type Ia/IIn(Ia) supernovae SN 2002ic and SN 2005gj, as well as the tenuous CSM around the normal Type Ia supernova SN 2006X. Our new model suggests the presence of very young (\(\leq 10^5\) yr) populations of SNe Ia, which is consistent with recent observational indications of young-population SNe Ia.

Subject headings: binaries: close — circumstellar matter — stars: winds, outflows — supernovae: individual (SN 2002ic, SN 2005gj, SN 2006X)

1. INTRODUCTION
The nature of Type Ia supernova (SN Ia) progenitors has not been clarified yet (e.g., Hillebrandt & Niemeyer 2000; Nomoto et al. 2000), although it has been commonly agreed that the exploding star is a mass-accreting carbon-oxygen white dwarf (C+O WD). For the exploding WD itself, the observed features of SNe Ia are better explained by the Chandrasekhar mass model than by the sub-Chandrasekhar mass model (e.g., Livio 2000). However, there has been no clear observational indication as to how the WD mass gets close enough to the Chandrasekhar mass for carbon ignition to occur; i.e., whether the WD accretes H/He-rich matter from its binary companion (the single degenerate [SD] scenario), or two C+O WDs merge (the double degenerate [DD] scenario).

Recently, the following two important findings have been reported in relation to SN Ia progenitors: (1) the presence of circumstellar matter (CSM) around the progenitors, and (2) a very young (\(\leq 10^5\) yr) population of the progenitors.

Circumstellar matter.— In the SD scenario, H/He-rich CSM is expected to exist around SNe Ia as a result of mass transfer from the companion, as well as the WD winds (e.g., Nomoto 1982; Hachisu et al. 1999a). Thus, the detection of H/He-rich CSM is one of the key observations with which to identify the progenitors (e.g., Lundqvist et al. 2003). Recently, detections of such CSM have been reported for several SNe Ia: i.e., observations of narrow H emission lines in SN 2002ic (Hamuy et al. 2003) and SN 2005gj (Alderling et al. 2006; Prieto et al. 2007; Type Ia/IIn or Ia: Deng et al. 2004), thermal X-rays from SN 2005ke (Immler et al. 2006), and Na i D lines in SN 2006X (Patat et al. 2007a).

The identification of SN 2002ic as an SN Ia has been confirmed by the recent spectral comparison between SN 2005gj and SNe Ia (Prieto et al. 2007), in contrast to the Type Ic suggestion made by Benetti et al. (2006). Several CSM interaction models have suggested a 1–2\(M_\odot\) CSM (Chugai et al. 2004; Nomoto et al. 2005). The evolutionary origin of such a massive CSM has been explored by Livio & Reiss (2003) on the basis of a common envelope evolution model, by Han & Podsiałowski (2006) on the basis of the delayed dynamical instability model of binary mass transfer, and by Wood-Vasey & Sokoloski (2006) on the basis of a recurrent nova model with a red giant companion.

For normal SNe Ia, the nondetection of radio has put the upper limit of the mass-loss rate at \(\dot{M}/\nu_{10} \leq 10^{-8}\ M_\odot\ yr^{-1}\), where \(\nu_{10} \equiv \nu/10\ km\ s^{-1}\) (Panagia et al. 2006). However, the optical observations of SN 2006X have detected variable Na i D lines from the CSM, whose expansion velocity and mass have been estimated to be \(\nu_{10} \sim 10\) and \(\sim 10^{-4}\ M_\odot\) (Patat et al. 2007a). Patat et al. have suggested that the CSM in SN 2006X originated from the red giant companion because of its relatively low velocities. Comparing the SN 2006X light curves with the other normal SNe Ia light curves, Wang et al. (2008b) suggested that the obvious deviation, which is that the decline rate slows down in a later phase, can be explained by an interaction between the ejecta and the CSM or a light echo of circumstellar/interstellar matter (see also Wang et al. 2008a).
Young population.— According to Mannucci et al. (2006), the present observational data of SNe Ia are best matched by a bimodal population of the progenitors, in which about 50% of SNe Ia explode soon after their stellar birth at a delay time of $t_{\text{delay}} \sim 10^8$ yr, while the remaining 50% have a much wider distribution of the delay time of $t_{\text{delay}} \sim 3$ Gyr. Aubourg et al. (2007) recently reported evidence for a short (less than 70 Myr) delay time component in the SN Ia population. In this paper, we define the term “delay time” as the age of a binary system at the SN Ia explosion, in order to compare our results with earlier results (e.g., Greggio & Renzini 1983; Greggio 2005; Mannucci et al. 2006).

These kinds of short delay times ($t_{\text{delay}} \leq 10^8$ yr) for SNe Ia have been suggested from the distribution of SNe Ia relative to galactic spiral arms (e.g., Bartunov et al. 1994; Della Valle & Livio 1994). Recently, Di Stefano & Kong (2003) reported, on the basis of Chandra data from four external galaxies (an elliptical galaxy, NGC 4967; two face-on spiral galaxies, M101 and M83; and an interacting galaxy, M51), that in every galaxy there are at least several hundred luminous supersoft X-ray sources (SSXSs) with a luminosity of $\geq 10^{37}$ erg s$^{-1}$ and that in the spiral galaxies M101, M83, and M51, the SSXSs appear to be associated with the spiral arms. The latter may indicate that SSXSs are young systems, possibly younger than $10^8$ yr, and may have some close relation to the young population of SNe Ia.

The SD scenario has not yet predicted such young populations as $t_{\text{delay}} \sim 10^8$ yr, which corresponds to, at least, zero-age main-sequence (ZAMS) stars at masses of $5\rightarrow 6 M_\odot$ (see, e.g., Li & van den Heuvel 1997; Hachisu et al. 1999b; Langer et al. 2000; Han & Podsadiłowski 2004). In the present paper, we propose a scenario for such a young SN Ia population by introducing the mass-stripping effect into binary evolutions. Mass-accreting WDs blow optically thick winds when the mass transfer rate to the WD begins. This mass transfer occurs in a thermal phase (see, e.g., Li & van den Heuvel 1997; Hachisu et al. 1999b; Langer et al. 2000; Han & Podsadiłowski 2004). In the present paper, we propose a scenario for such a young SN Ia population by introducing the mass-stripping effect into binary evolutions. Mass-accreting WDs blow optically thick winds when the mass transfer rate to the WD exceeds the critical rate of $M_0 \sim 1 \times 10^{-6} M_\odot$ yr$^{-1}$ (Hachisu et al. 1996). The WD wind collides with the secondary’s surface and strips off matter. When the mass-stripping effect is efficient enough, the mass transfer rate to the WD is attenuated and the binary can avoid the formation of a common envelope, even for a rather massive secondary.

The mass-stripping effect on a MS companion was first introduced by Hachisu & Kato (2003b, 2003c), who analyzed two quasi-periodic transient supersoft X-ray sources, RX J0513.9–6951 and V Sge. RX J0513 shows a quasi-periodic oscillation between optical high ($\sim 100$–120 days) and low ($\sim 40$ days) states with an amplitude of 1 mag (Alcock et al. 1996), and it is X-ray–bright only during the optical low states (Reinsch et al. 2000). Hachisu & Kato (2003b) proposed a model in which the mass transfer is modulated by the WD wind because the WD wind collides with the companion and strips off its surface, thus attenuating the mass transfer rate. When the mass transfer rate decreases below the critical rate $M_0$, the WD wind stops and the supersoft X-ray emission turns on. This corresponds to an optical low state. Then the mass transfer rate recovers because of the absence of attenuation by WD winds, and the WD blows winds again. The X-ray emission turns off, an optical high state resumes, and the binary starts the next cycle of quasi-periodic oscillation. Such a self-sustaining model naturally explains major characteristics of quasi-periodic high and low states, and this success encourages us to adopt the same idea in the evolution scenario of supersoft X-ray sources and SN Ia progenitors.

In the present paper, we show that this mass-stripping effect results in (1) formation of circumstellar matter around SNe Ia and (2) a very young population of SNe Ia. We summarize our basic treatments of the mass-stripping effect and binary evolutions in §2 and then show our numerical results and their relations to a very young population of SNe Ia in §3. In §4 we present the origin of the CSM around SNe Ia on the basis of our results and describe a relation between the very young population of SNe Ia and their massive CSM. Discussion and concluding remarks follow in §§5 and 6.

2. THE MASS-STRIPPING EFFECT AND BINARY EVOLUTION

Strong winds from a mass-accreting WD collide with the companion star and strip off its surface. This mass-stripping effect plays an important role in binary evolutions (e.g., Hachisu et al. 1999a). Here we reformulate its treatment in our binary evolution calculations.

2.1. New Aspects of Binary Evolutions

First we briefly introduce a new binary evolutionary process through the four stages below (shown in Fig. 1), where the third and fourth are new stages introduced by mass stripping.

1. The more massive (primary) component of a binary evolves to a red giant star (with a helium core) or an AGB star (with a C+O core) and fills its Roche lobe. Mass transfer from the primary to the secondary begins, and a common envelope is formed. After the first common envelope evolution, the separation shrinks and the primary component becomes a helium star or a C+O WD. The helium star evolves to be a C+O WD after a large part of the helium is exhausted by core helium burning. We eventually have a close pair of a C+O WD and a main-sequence star, as shown in Figure 1a.

2. After the secondary evolves to fill its Roche lobe, the mass transfer to the WD begins. This mass transfer occurs in a thermal timescale because the secondary is more massive than the WD. The mass transfer rate exceeds the critical rate for the optically thick wind to blow from the WD (Hachisu et al. 1996, 1999a, 1999b).

3. Optically thick winds from the WD collide with the secondary and strip off its surface layer (Hachisu & Kato 2003a, 2003b, 2003c). This mass stripping attenuates the rate of mass transfer from the secondary to the WD, thus preventing the formation of a common envelope for a more massive secondary in the case with this effect than in the case without this effect. Thus, the mass-stripping effect widens the donor mass range of SN Ia progenitors (see Fig. 3 below).

4. Such stripped-off matter forms a massive circumstellar torus on the orbital plane, and it may be gradually expanding with an outward velocity of $\sim 100$ km s$^{-1}$ (Fig. 1d), because the escape velocity from the surface of the secondary to the L3 point is $v_{\text{esc}} \sim \left[ (\phi_{\text{L3}} - \phi_{\text{MS}}) GM_2 / a \right]^{1/2} \sim 100$ km s$^{-1}$ (see below). Subsequent interactions between the fast wind from the WD and the very slowly expanding circumbinary torus form an hourglass structure (see Figs. 1c–1d).

2.2. Formulation of Mass Stripping

Fast strong winds collide with the companion, as illustrated in Figure 1. The companion’s surface gas is shock-heated and ablated by the wind. We estimate the effect of the shock heating by assuming that the velocity component normal to the companion’s surface is dissipated by the shock and that the kinetic energy is converted into the thermal energy of the surface layer. The heated surface layer expands to be ablated in the wind.

To obtain the mass-stripping rate, we use the same formulation proposed by Hachisu & Kato (2003b, 2003c). We equate the
stripping rate times the gravitational potential at the companion surface to the net rate of energy dissipation by the shock:

$$\frac{GM}{a} (\phi_{L3} - \phi_{MS}) \dot{M}_{\text{strip}} = \frac{1}{2} v^2 \eta_{\text{eff}} g(q) \dot{M}_{\text{wind}}, \quad (1)$$

where $M = M_{\text{WD}} + M_{\text{MS}}$, $M_{\text{WD}}$ is the WD mass, $M_{\text{MS}}$ is the main-sequence companion mass, $a$ is the separation of the binary, $\phi_{MS}$ and $\phi_{L3}$ denote the Roche potential (normalized by $GM/a$) at the companion surface and the L3 point near the MS companion, respectively, $v$ is the WD wind velocity, $\eta_{\text{eff}}$ is the efficiency of the conversion from kinetic energy to thermal energy by the shock, $g(q)$ is the geometrical factor of the companion’s surface hit by the wind, including the inclination (oblique shock) effect of the wind velocity against the companion’s surface [see Hachisu et al. (1999a) for more details on $g(q)$], and $q \equiv M_2/M_1 = M_{\text{MS}}/M_{\text{WD}}$ is the mass ratio. Here we modified equation (21) of Hachisu et al. (1999a) to include the effect of Roche lobe overflow from the L3 point. Then the stripping rate is estimated as

$$\dot{M}_{\text{strip}} = c_1 \dot{M}_{\text{wind}}, \quad (2)$$

$$c_1 = \frac{\eta_{\text{eff}} g(q)}{\phi_{L3} - \phi_{MS}} \frac{v^2 a}{2GM}. \quad (3)$$

Here we assume that the WD wind is spherically symmetric. If the asphericity of the WD wind is not too large, with a latitudinal ($\theta$ angle) dependency like that of a broad-angle jet, we have a different form of $g(q)$, and its value may be much smaller than that for the spherically symmetric WD winds. We also assume $\eta_{\text{eff}} = 1$ in the present calculation. When the wind velocity is as fast as 4000 km s$^{-1}$, we have $c_1 \sim 10$, as estimated by Hachisu & Kato (2003b). Although there is a large ambiguity in this kind of parameterization for $c_1$, Hachisu & Kato (2003b, 2003c) found the best-fit models with values of $c_1 = 1.5$–$10$ for RX J0513.9–6953 and $c_1 = 7$–$8$ for V Sge. We thus assume values of $c_1 = 1$, 3, and 10 in order to examine the dependence of our model on the mass-stripping effect, because the essential ambiguity of our formulation is included in the $c_1$ parameter.

When winds blow from the WD and strip off the companion’s surface, the change of the separation, $\dot{a}$, is calculated as

$$\dot{a} = \frac{M_1 + M_2}{M_1 + M_2} \frac{2M_1}{M_1} - 2 \frac{M_2}{M_2} + 2 \frac{J}{J},$$

$$= \frac{M_1 + M_2}{M_1 + M_2} \left( \frac{2M_1}{M_1} - 2 \frac{M_2}{M_2} \right) + 2 \frac{M_1 + M_2}{M_1 M_2} (l_w \dot{M}_{\text{wind}} + l_s \dot{M}_{\text{strip}}), \quad (4)$$

where $M_1 = M_{\text{WD}}$, $M_2 = M_{\text{MS}}$, and $l_w$ and $l_s$ are the specific angular momenta of the WD wind and the stripped-off matter, respectively, in units of $a^2 \Omega_{\text{orb}}$, where $\Omega_{\text{orb}}$ is the orbital angular velocity. Since the WD wind is much faster than the orbital motion, the wind cannot get angular momentum from the orbital torque during its journey, so the wind has the same specific angular momentum as the WD, which is estimated as

$$l_w = \left( \frac{q}{1 + q} \right)^2. \quad (5)$$

The ablated gas from the companion is assumed to have the same angular momentum as that at the companion’s surface. Then we have a numerical factor of

$$l_s = \frac{h(q)}{g(q)}, \quad (6)$$

which was given in Table 1 of Hachisu et al. (1999a) and is rather small compared with $l_w$. (See Hachisu et al. [1999a] for more details of $l_s$.)

2.3. Modified Mass Transfer Rate

We have followed binary evolutions from the initial state of $(M_{1,0}, M_{2,0}, P_0)$ [i.e., $(M_{\text{WD,0}}, M_{\text{MS,0}}, P_0)$], where $P_0$ is the initial orbital period. Here, the subscript naught (“0”) denotes the first stage in Figure 1; that is, before the mass transfer from the secondary starts. The radius, $R_2(M_2, t)$, and luminosity, $L_2(M_2, t)$, of stars that have slightly evolved off the zero-age main-sequence are calculated using the analytic form given by Tout et al. (1997).
The mass transfer proceeds on a thermal timescale when the mass ratio \( M_2/M_1 \) exceeds 0.79. We approximate the mass transfer rate as

\[
\dot{M}_2 = \frac{M_2}{\tau_{\text{KH}}} \max\left( \frac{\zeta_{\text{RL}} - \zeta_{\text{MS}}}{\zeta_{\text{MS}}}, 1 \right),
\]  

(7)

where \( \tau_{\text{KH}} \) is the Kelvin-Helmholtz timescale given by (e.g., Paczyński 1971)

\[
\tau_{\text{KH}} \approx (3 \times 10^7 \text{ yr}) \left( \frac{M_2}{M} \right)^2 \left( \frac{R_2 L_2}{R_L L} \right)^{-1}
\]  

(8)

and \( \zeta_{\text{RL}} = d \log R'/d \log M \) and \( \zeta_{\text{MS}} = d \log R_{\text{MS}}/d \log M \) are the radius-mass exponents of the inner critical Roche lobe and the main-sequence component, respectively (e.g., Hjellming & Webbink 1987). The effective radius of the inner critical Roche lobe, \( R^* \), is calculated from Eggleton’s (1983) empirical formula:

\[
\frac{R^*}{a} = f(q) = \left( \frac{0.49 q^{3/2}}{0.6 q^{2/3} + \ln (1 + q^{1/3})} \right)
\]  

(9)

where \( q = M_2/M_1 \).

When the mass transfer rate to the WD exceeds a critical value, which is given by

\[
\dot{M}_{\text{cr}} \approx 0.75 \times 10^{-6} \left( \frac{M_{\text{WD}}}{M_\odot} - 0.4 \right) M_\odot \text{ yr}^{-1}
\]  

(10)

for a solar composition (hydrogen content of \( X = 0.7 \) and metallicity of \( Z = 0.02 \)), the WD blows a wind with a mass-loss rate of \( M_{\text{wind}} \) \(<0\). This critical rate of \( \dot{M}_{\text{cr}} \) is the same as the critical rate for mass-accreting WDs to be able to expand to giant size; i.e., \( M_{\text{RG}} \) (see Nomoto et al. [2007] for a recent calculation of \( M_{\text{RG}} \)). The mass loss from the WD also occurs during the hydrogen shell flashes when \( -\dot{M}_2 < \dot{M}_{\text{sb}} \), where \( \dot{M}_{\text{sb}} \) is the lowest rate for steady hydrogen burning and is given by (Nomoto et al. 2007)

\[
\dot{M}_{\text{sb}} \approx 0.31 \times 10^{-6} \left( \frac{M_{\text{WD}}}{M_\odot} - 0.54 \right) M_\odot \text{ yr}^{-1}
\]  

(11)

When \( \dot{M}_{\text{sb}} < -\dot{M}_2 < \dot{M}_{\text{cr}} \), there is no mass loss associated with steady hydrogen shell burning, but there is mass lost through helium shell flashes. This mass loss plays some role in the binary evolution (Kato & Hachisu 1999). Therefore, \( M_{\text{wind}} \) is the sum of the optically thick wind mass loss, the hydrogen shell flashes, and the helium shell flashes.

We have the relation

\[
\dot{M}_1 + \dot{M}_2 = \dot{M}_{\text{wind}} + \dot{M}_{\text{strip}}
\]  

(12)

from the total mass conservation, which thus defines the net mass transfer rate to the WD as

\[
\dot{M}_\text{tr} = \dot{M}_{\text{strip}} - \dot{M}_2 = \dot{M}_1 - \dot{M}_{\text{wind}},
\]  

(13)

where values of \( \dot{M}_0 > 0, \dot{M}_{\text{strip}} \leq 0, \dot{M}_2 < 0, \dot{M}_1 \geq 0, \) and \( \dot{M}_{\text{wind}} \leq 0 \) should be noted. If \( \dot{M}_2 \) is given, we have a net mass transfer rate of

\[
\dot{M}_\text{tr} = \begin{cases} 
(c_1 \dot{M}_2 - \dot{M}_1)/c_1 + 1 \quad & \text{for} \quad -\dot{M}_2 > \dot{M}_{\text{cr}}, \\
-\dot{M}_2 \quad & \text{for} \quad -\dot{M}_2 \leq \dot{M}_{\text{cr}},
\end{cases}
\]  

(14)

where we use equation (2), equation (13), and the relation

\[
-\dot{M}_{\text{wind}} = \dot{M}_\text{tr} - \dot{M}_{\text{cr}}
\]  

(15)

for \( -\dot{M}_2 > \dot{M}_{\text{cr}} \). Other treatments for binary evolution are essentially the same as those in Hachisu et al. (1999b).

Figure 2 shows two typical evolutionary sequences that demonstrate the effects by the modified mass transfer rate, \( \dot{M}_2 \), in equation (7).

Case WIND.— Starting from \( M_{\text{WD,0}} = 1.0 M_\odot, M_{2,0} = 5.0 M_\odot, \) and \( P_0 = 2.15 \) days, with \( c_1 = 3 \), the WD reaches the SN Ia explosion in the wind phase (case WIND) at \( t = 6.57 \times 10^5 \) yr after the secondary fills its Roche lobe. The WD increases its mass (\( M_{\text{WD}} \)) up to \( M_{\odot} = 1.38 M_\odot \) to explode as an SN Ia. The secondary mass (\( M_2 \)) decreases to 2.01 \( M_\odot \) at the time of the explosion. Both the mass-loss rate of the secondary (dashed line labeled \( M_2 \)) and the WD wind mass-loss rate (dashed line labeled \( M_{\text{wind}} \)) are also decreasing rapidly, especially in the early phase when \( t \approx 1 \times 10^5 \) yr. This is because \( -\dot{M}_2 \) is large and the mass transfer rate, \( \dot{M}_\text{tr} \), is large during this phase, and as a result, both the WD wind mass-loss rate, \( M_{\text{wind}} \), and the stripping rate, \( \dot{M}_{\text{strip}} \), are also large. Shortly after this early phase, the Roche lobe’s radius-mass exponent, \( \zeta_{\text{RL}} \), becomes smaller than the secondary’s radius-mass exponent, \( \zeta_{\text{MS}} \); that is, \( \zeta_{\text{RL}} - \zeta_{\text{MS}} < 0 \). This gives \( -\dot{M}_2 = M_2/\tau_{\text{KH}} \) from equation (7). We keep this mass transfer rate for as long as the secondary overfills its Roche lobe; i.e., \( R_2 > R_2^* \). In Figure 2a, we plot the secondary radius (red line labeled \( R_2 \)) and the Roche lobe radius for the secondary component (blue line labeled \( R_2^* \)) to show the condition of \( R_2 > R_2^* \) during the evolution.

Case CALM.— Starting from \( M_{\text{WD,0}} = 1.0 M_\odot, M_{2,0} = 5.0 M_\odot, \) and \( P_0 = 6.79 \) days, with \( c_1 = 3 \), the WD reaches the SN Ia explosion, in a phase of no winds (case CALM), at \( t = 6.93 \times 10^5 \) yr after the secondary fills its Roche lobe. In this case, the evolution of the mass transfer rate is different from that in case WIND above. With \( -\dot{M}_2 = M_2/\tau_{\text{KH}} \) for \( \zeta_{\text{RL}} - \zeta_{\text{MS}} < 0 \) in equation (7), the secondary eventually no longer fills the Roche lobe; i.e., \( R_2 < R_2^* \). This can be seen in Figure 2b, where the line of \( R_2 \) crosses the line of \( R_2^* \) at \( t \approx 1 \times 10^5 \) yr. This is because the stripped matter has a rather low specific angular momentum (eq. [6]), such that the binary separation hardly shrinks or even increases, as can be seen from the temporal increase in the orbital period in Figure 2b. In realistic binary evolutions, the mass transfer is tuned in such a way that the secondary radius is always equal to the Roche lobe radius for the secondary, i.e., \( R_2 = R_2^* \). Therefore, \( -\dot{M}_2 \) is drastically decreased after \( t \approx 1 \times 10^5 \) yr, as is shown in Figure 2b. Thus, the optically thick WD wind stops at \( t = 5.5 \times 10^5 \) yr. In such a low mass transfer phase as \( \dot{M}_2 \approx 1 \times 10^{-8} M_\odot \text{ yr}^{-1} \), weak helium shell flashes occur and play an important role as a mass-loss mechanism. This helium flash wind also strips off the secondary surface, thus working as a stripping effect. We introduce the mass-stripping effect by these helium shell flashes into our binary evolution. Very small but nonzero values of \( M_{\text{wind}} \) in Figure 2b (after the winds stop) represent the mass loss from the WD due to helium shell flashes, and \( \dot{M}_2 \) includes the ensuing mass stripping from the secondary.

3. YOUNG-POPULATION TYPE Ia SUPERNOVAE

On the basis of the binary evolution scenario proposed by Hachisu et al. (1999a, 1999b), we have followed binary evolutions starting from the second stage in Figure 1: that is, when the companion first evolves to fill its Roche lobe. The main difference from the previous work cited above is the inclusion of the mass-stripping effect. Our results are shown in Figures 3—10.

Figure 3 shows the parameter regions that produce SNe Ia (the “SN Ia region”) in the log \( P_0 - M_{2,0} \) (initial orbital period and initial secondary mass) plane for the WD + MS system. Here the initial white dwarf mass is assumed to be \( M_{\text{WD,0}} = 1.0 M_\odot \). The white dwarfs within these SN Ia regions will increase their mass, \( M_{\text{WD}} \), up to the critical mass \( (M_\text{tr} = 1.38 M_\odot) \) for the SN Ia explosion to occur.
The SN Ia region in the log $P_0$--$M_{2,0}$ plane is enclosed by four boundaries. (1) The left boundary is given by the mass-radius relation for the zero-age main-sequence stars. (2) The lower boundary is set by strong nova explosions, below which $\dot{M}_{\text{tr}}$ and the resultant nova explosion ejects most of the accreted matter, thus preventing the WD mass from increasing. (3) The upper boundary is set by the formation of a common envelope. Here we assume that a common envelope is formed when $\dot{M}_{\text{tr}} > \frac{1}{4} \times 10^{-6} \frac{M_\odot}{\text{yr}}$ because $R_1 \approx 10 R_\odot$ for such a high value of $\dot{M}_\text{tr}$, where $R_1, \text{ph}$ is the radius of the photosphere of the white dwarf (the primary component; see Hachisu et al. [1999b] for more details). (4) The right boundary corresponds to the end of central hydrogen burning of the MS companion; after that, it shrinks and no longer fills its Roche lobe.

In Figure 3, the SN Ia regions for the various mass-stripping factor values of $c_1 = 10, 3, 1$ are circled by the thick, medium, and thin solid lines, respectively, and the case with no stripping ($c_1 = 0$) is indicated by the dotted line. The position
Fig. 3.—Initial parameter regions producing SNe Ia, plotted in the log $P_0$–$M_{2,0}$ (orbital period–donor mass) plane for the WD + MS systems with various mass-stripping factors $c_1$. Thick solid line: $c_1 = 10$. Medium solid line: $c_1 = 3$. Thin solid line: $c_1 = 1$. Dotted line: $c_1 = 0$. The red hatched region indicates a region with short delay times ($t_{\text{delay}} \leq 100$ Myr) for the case of $c_1 = 10$. The region extends to the more massive donors for the larger values of $c_1$. Two supersoft X-ray sources, RX J0513.9–6951 (open circle) and V Sge (filled circle), are plotted, the masses of which are estimated to be 2.7 $M_\odot$ (Hachisu & Kato 2003b) and 3.5 $M_\odot$ (Hachisu & Kato 2003c), and the orbital periods of which have been determined to be 0.76 days (Pakull et al. 1993) and 0.51 days (Herbig et al. 1965; Patterson et al. 1998), respectively. The position of V Sge suggests that $c_1 > 0$.

Fig. 4.—Dependence of the SN Ia parameter region on the initial WD mass, $M_{\text{WD,0}}$, for a mass-stripping factor of $c_1 = 3$. From inside to outside, $M_{\text{WD,0}} = 0.7, 0.8, 0.9, 1.0$ (thick solid line), and 1.1 $M_\odot$. There is no region shown for $M_{\text{WD,0}} = 0.6 M_\odot$. The red sparsely hatched region indicates delay times of $t_{\text{delay}} \leq 100$ Myr for $M_{\text{WD,0}} = 1.1 M_\odot$ and the blue densely hatched region shows those for $M_{\text{WD,0}} = 0.7 M_\odot$. 
Fig. 5.—Parameter regions that produce SNe Ia, plotted in the $\log P$–$M_d$ (orbital period–donor mass) plane for the WD + MS systems. Here we assume a value of $M_{\text{WD},0} = 1.1 \ M_\odot$ for the initial white dwarf mass. The initial WD + MS system, which will occur inside the region encircled by the thin red solid line (labeled “initial”), will increase its white dwarf mass up to the critical mass ($M_c = 1.38 \ M_\odot$) for the SN Ia explosion to occur. The final state of the WD + MS system just before the SN Ia explosion is encircled by the thick blue solid line (labeled “final”). The final state of the WD just before the SN Ia explosion is specified by one of the three recurrent novae, V394 CrA (Schaefer 1990) and CI Aql (Mennickent & Honeycutt 1995), which have unknown companion masses. The WD masses of U Sco and V394 CrA were estimated to be $1.37 \ M_\odot$ (Hachisu et al. 2000a; Hachisu & Kato 2000), whereas that of CI Aql was $1.2 \ M_\odot$ (Hachisu & Kato 2003a).

Galaxy as $\nu_{\text{WD+MS}} \sim 0.004 \ \text{yr}^{-1}$, which is consistent with observations (Cappellaro et al. 1999).

On the other hand, Hachisu et al. (1999a) proposed another channel to SNe Ia: the symbiotic channel, the binary of which consists of a white dwarf and a red giant (WD + RG), and they estimated its birth rate to be $\nu_{\text{WD+RG}} \sim 0.002 \ \text{yr}^{-1}$.

Assuming the initial distribution of binaries given by equation (16) at the burst of star formation (single event), we estimate the delay time distribution of SNe Ia for the WD + MS systems in Figure 11. The number ratio of these young populations is calculated for 10 bins of delay time: $(0.025, 0.05)$, $(0.05, 0.1)$, $(0.1, 0.2)$, $(0.2, 0.4)$, $(0.4, 0.8)$, $(0.8, 1.6)$, $(1.6, 3.2)$, $(3.2, 6.4)$, $(6.4, 12.8)$, and $(12.8, 25.6) \ \text{Gyr}$. The number ratios with $t_{\text{delay}} \leq 100 \ \text{Myr}$ and $t_{\text{delay}} \leq 200 \ \text{Myr}$ are about 50% and 80%, respectively, of the total SNe Ia coming from the WD + MS system, which is consistent with recent observational suggestions (e.g., Mannucci et al. 2006; Aubourg et al. 2007).

Short delay times ($t_{\text{delay}} \leq 10^8 \ \text{yr}$) for some SNe Ia have been suggested from the distribution of SNe Ia relative to spiral arms (e.g., Bartunov et al. 1994; Della Valle & Livio 1994). Petroset al. (2005) reported that about 30%–40% of SNe Ia are associated with spiral arms in their samples, which is consistent with our results. Mannucci et al. (2006) have suggested that the delay time distribution function of SNe Ia is bimodal, with one peak for young populations ($t_{\text{delay}} \sim 100 \ \text{Myr}$) and the other peak having a broad distribution over $\sim 3 \ \text{Gyr}$. Our delay time distribution function has a peak around $t_{\text{delay}} \leq 100 \ \text{Myr}$ from the WD + MS systems and a...
Fig. 6.—Final SN Ia region just before a SN Ia explosion. Each symbol has the same meaning as in Fig. 5. The upper solid black line and lower solid magenta line denote the values for which $-M_L = M_2$ and $-M_L = M_{\text{sn}}$, respectively, just at the SN Ia explosion, where $M_L$ is calculated from eq. (17), using values of $R_2$ and $L_2$ from a single-star evolution given by Tout et al. (1997). The lines agree reasonably with the borders of the WIND-CALM and CALM-RN regions, respectively.

Fig. 7.—Same as Fig. 5, but for an initial WD mass of $M_{\text{WD,0}} = 1.0 M_\odot$. 
**Fig. 8.**—Same as Fig. 6, but for an initial white dwarf mass of $M_{\text{WD},0} = 1.0\, M_\odot$. The large difference in the border of the WIND-CALM regions comes from the fact that the secondary considerably overfills the Roche lobe, i.e., $R_2 > R_2^c$, at the SN Ia explosion in case WIND.

**Fig. 9.**—Same as Fig. 5, but for an initial white dwarf mass of $M_{\text{WD},0} = 0.9\, M_\odot$. There is no case WIND (no circles).
broad distribution from the WD + RG systems (Hachisu et al. 1999a; Hachisu & Kato 2001), as is shown in Figure 12.

4. FINAL STAGE OF BINARY EVOLUTION AND CIRCUMSTELLAR MATTER

The final state of the WD depends mainly on the mass transfer rate $\dot{M}$ from the donor star to the WD at the SN Ia explosion (Nomoto 1982; Hachisu et al. 1999a; Nomoto et al. 2007). As is shown in Figure 2, $\dot{M}$ drops quickly in the early stage and then slows down to almost a constant value. At least in the early phase, the mass transfer proceeds on a thermal timescale, represented by the second term of equation (7), when the mass ratio $M_2/M_1$ exceeds 0.79. Thus, we approximate the mass transfer rate as

$$\dot{M}_2 = \frac{C_0}{C_25} M_2^{C_{28}/C_{24}^2} \frac{M_2^{C_{18}/C_{19}}} R_2^{C_{12}/C_{11}} L_2^{C_{12}/C_{11}} M_2^{C_{12}/C_{11}}.$$  

(17)

By applying the approximate $M_2$-$L_2$ relation of $L_2 \propto M_2^m$ for the 1.5–3 $M_\odot$ ZAMS stars or $m \sim 4$ for the 3–7 $M_\odot$ ZAMS stars,

$$-\dot{M}_2 \propto R_2 M_2^{m-1}.$$  

(18)

Thus, $-\dot{M}_2$ decrease as $M_2$ decreases.

Figures 5–10 show the SN Ia regions in the log $P$-$M_d$ (orbital period–donor mass) plane for the initial WD + MS system (encircled by the thin red line and labeled “initial”), as well as the final state at the SN Ia explosion (encircled by the thick blue line and labeled “final”). Here we assume that $c_1 = 3$ and $M_{W,0} = 1.1, 1.0, and 0.9 M_\odot$. In these figures, we distinguish three final states just before the SN Ia explosion: i.e., the optically thick WD wind phase (case WIND; circles), the steady hydrogen burning phase without optically thick winds from WDs (case CALM; triangles), and the recurrent nova (RN) phase (case RN; squares).

The characteristic properties for these three progenitor stages are summarized in Table 1, and the corresponding binary parameters are tabulated in Table 2.

4.1. Case WIND

When the mass transfer rate from the secondary continuously exceeds the critical rate of equation (10) until the final stage, the
WDs explode during the wind phase (Fig. 2a). Therefore, we call this “case WIND.” Case WIND is realized in the region of $M_{2,0} \gtrsim 3 \, M_\odot$ and $P_{2,0} \lesssim 2$ days for $M_{WD,0} = 1.1$ and $1.0 \, M_\odot$ (Figs. 5–8, circles), but no case WIND exists for $M_{WD,0} \lesssim 0.9 \, M_\odot$, as shown in Figures 9 and 10.

The stripped-off matter from the companion can easily amount to $\Delta M_{\text{strip}} \sim 1$–$2 \, M_\odot$, and can even reach 3–$4 \, M_\odot$, as can be seen from the donor mass difference $\Delta M_2$ between the “initial” and “final” regions in Figures 5, 7, and 9. More precisely, the quantity $\Delta M_2$ consists of three parts: the stripped-off mass, $\Delta M_{\text{strip}}$, the accreted mass by the WD, $\Delta M_1$, and the mass ejected by the WD wind, $\Delta M_{\text{wind}}$; i.e., $M_2 = M_{\text{strip}} + M_{\text{wind}} - M_1$ from equation (12). This can be approximated as $M_2 \approx M_{\text{strip}} + M_{\text{wind}} = (1 + 1/c_1)M_{\text{strip}} = (4/3)M_{\text{strip}}$ because $M_1 \ll -M_2$, so that $\Delta M_{\text{strip}} \approx (3/4)\Delta M_2$ for $c_1 = 3$.

The stripped-off material forms CSM very near the SN Ia. We expect that stripped-off matter does not go away from the system because the velocity of the stripped-off matter may not exceed the escape velocity of the binary system. Then the SN Ia undergoes circumstellar interaction, as observed in the Type Ia/IIIn (or IIn) supernovae SN 2002ic and SN 2005gj.

Alderling et al. (2006) suggested that the host galaxy of SN 2005gj had a burst of star formation $200 \pm 70$ Myr ago. If the progenitor of SN 2005gj was born at that time, its delay time is consistent with our case WIND, as is shown in Figure 11.

### 4.2. Case CALM

When the mass transfer rate from the secondary is below the critical rate for optically thick winds but above the lowest rate of steady hydrogen burning, i.e., $M_{\text{sh}} < M_\odot < M_{\text{cr}}$, the WDs undergo steady H burning at the time of the SN Ia explosion (Figs. 5–10, triangles). We call this “case CALM” because no optically thick winds occur. The WDs are observed as supersoft X-ray sources until the SN Ia explosion. The stripped-off material forms CSM, but it has been dispersed too far for it to be detected immediately after the SN Ia explosion.

The CALM case is realized in the region of $M_{2,0} \gtrsim 3 \, M_\odot$ and $P_{2,0} \lesssim 2$ days for $M_{WD,0} = 1.1$ and $1.0 \, M_\odot$ in Figures 5 and 7, where the value of $M_\odot$ in the early phase is much larger than that for $P_{2,0} \lesssim 2$ days, because in equations (7) and (17), the values of $R_2$ and $L_2$ are much larger than those for $P_{2,0} \lesssim 2$ days. Then the value of $M_\odot$ is much larger; thus, much more mass had been lost in the earlier phase. As a result, the wind phase finishes at an earlier time even for the same initial mass $M_{2,0}$, as can be seen in Figure 2. Therefore, in which the SN Ia mass explosion, no wind occurs.

In the region in which $M_{2,0} \lesssim 3 \, M_\odot$ for $M_{WD,0} = 1.1$ and $1.0 \, M_\odot$ in Figures 5–8 (triangles and squares, respectively), $M_2$ decreases to as small as the primary’s $M_{WD,0}$, i.e., the mass ratio of $q < 1$, at the SN Ia explosion, which corresponds to a lower part of the “final” region. Then the mass transfer rate decreases down to $M_{\text{sh}} < M_{\text{cr}}$, or even $M_{\text{sh}} < M_{\text{sh}}$, because $L_2$ is smaller for the smaller value of $M_2$, even if the mass transfer itself is proceeding on a thermal timescale. The wind phase ends earlier than it does for $M_{2,0} \gtrsim 3 \, M_\odot$.

The border between case WIND and case CALM can be simply estimated from the conditions $M_\odot = M_\odot$, and $P_2 = P_2$ at the SN Ia explosion. We have calculated $M_\odot$ from equation (17) and have taken $R_2$ and $L_2$ from Tout et al. (1997; a single-star evolution). This line agrees reasonably with the border of WIND-CALM in Figure 6 but largely deviates from it in Figure 8. This is because the secondary considerably overfills the Roche lobe, i.e., $R_2 > R_2^*$, at the SN Ia explosion for $M_{WD,0} = 1.0 \, M_\odot$.

For $M_{WD,0} \lesssim 0.9 \, M_\odot$ (Fig. 9, triangles and squares), $M_2$ decreases at the SN Ia explosion, as shown in Figure 9 (“final” region), and $M_\odot$ decreases to be lower than $M_{\text{cr}}$, mainly because the time for the WD to reach $M_{\text{sh}} = 1.38 \, M_\odot$ is longer and much more mass is lost during the evolution. The wind phase ends before the SN Ia explosion.

For a typical case of $c_1 = 3$, $M_{WD,0} = 0.9 \, M_\odot$, $M_{2,0} = 4.0 \, M_\odot$, and $P_2 = 1.3$ days, as shown in Figure 9, the WD explodes as an SN Ia at $t = 9 \times 10^5$ yr after the secondary fills its Roche lobe. The wind has already stopped $3 \times 10^5$ yr ago (the duration of the wind phase is $\Delta P_{\text{wind}} = 6 \times 10^5$ yr, and the duration of the CALM phase is $\Delta P_{\text{calm}} = 3 \times 10^5$ yr), so the inner edge of the stripped-off material has already gone to a distance of $(10–100 \, \text{km} \, \text{s}^{-1})(3 \times 10^5 \, \text{yr}) \sim 10^{19}$–$10^{20}$ cm from the SN Ia. Therefore, it takes about $10–100$ yr for the SN Ia ejecta to reach the inner edge of the stripped-off matter. We do not expect radio or X-ray emission until at least $10–100$ yr after the explosion. Thus, the resultant SNe Ia are mostly “normal.” The duration of the CALM phase is typically one-third or one-fourth of the total evolution time to a SN Ia. These long durations of optically thick wind phases

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**TABLE 1**

| Case         | Wind   | Hydrogen Burning | CSM       | Pre-SN History | SN Ia  | Delay Time | Immediate Radio/X-Ray |
|--------------|--------|------------------|-----------|----------------|--------|------------|-----------------------|
| WIND......... | Wind   | Steady           | Massive: near | WIND (V Sge type) | IIa (SN 2002ic-like) | Young | Yes        |
| CALM......... | No wind| Steady           | Thin: far  | WIND—SSXS | Normal Ia | Young | No (~10–100 yr) |
| RN............ | No wind| Flash            | Very thin: many shells | WIND—SSXS—RN or SSXS—RN | Normal Ia | Broad | No (~100–1000 yr) |
may reduce the statistical number of luminous supersoft X-ray sources because the photospheric temperature of the WD is lower than $\sim 10$ eV and is not luminous in supersoft X-rays.

The decline of the SN 2006X light curves slows down in a later phase compared with the other normal SNe Ia light curves, which suggests an interaction between the ejecta and the CSM in a later phase (Wang et al. 2008b) or a light echo of circumstellar/interstellar matter (Wang et al. 2008a). This happens if SN 2006X is placed at the border between our case WIND and case CALM, since the innermost part of the slowly expanding circumstellar matter has not yet moved far away. A X-ray-detected supernova, SN 2005ke, may also belong to the same category (Immler et al. 2006).

For the progenitor of SN 2006X, Patat et al. (2007a) suggested a WD + RG system such as RS Oph from the circumstellar matter absorption lines. Here we suggest that a WD + MS system (such as U Sco) may better explain the continuous velocity distribution (from approximately $-30$ to $-150$ km s$^{-1}$) of the CSM absorption lines by the stripped matter with continuous velocity distribution (see Fig. 1d). In this connection, a very recent report of the Na I D circumstellar lines of RS Oph during the 2006 outburst is suggestive (Iijima 2008). These lines indicate no continuous distribution as observed in SN 2006X, but rather a narrow velocity component of $\sim 36$ km s$^{-1}$ against RS Oph that is attributed to the red giant cool wind.

Recently, negative detections of time-variable Na I D lines have been reported for two Type Ia supernovae, SN 2000cx (Patat et al. 2007b) and SN 2007af (Simon et al. 2007). Patat et al. (2007b) and Simon et al. (2007) suggested the possibility that the distribution of the CSM is torus/disk-like, as is illustrated in Figure 1. In such a case, variable Na I D lines would not be observed if the line of sight were perpendicular to or off the orbital plane. Since the hot WD winds have a large velocity of $\gtrsim 1000$ km s$^{-1}$, the CSM formed by hot winds would quickly diffuse away and would be too tenuous to be detected.

Also recently, Badenes et al. (2007) reported that a fast WD wind of $v \gtrsim 200$ km s$^{-1}$, which excavates its circumstellar medium and forms a large cavity around an SN Ia, is incompatible with the X-ray emission from the shocked ejecta in our Galaxy (Kepler, Tycho, SN 1006), the Large Magellanic Cloud (0509–67.5, 0519–69.0, N103B), and M31 (SN 1885). We can avoid this difficulty if the stripped-off matter has a velocity of $10$–$100$ km s$^{-1}$.

### 4.3. Case RN

When the mass transfer rate from the secondary is below the lowest rate of steady hydrogen burning, i.e., $M_t < M_{\text{acc}}$, hydrogen shell burning is unstable to flash, and this can recur many times in a short period as a recurrent nova (RN; Figs. 5–10, squares). We call this “case RN.” The recurrent nova U Sco, one of the candidates of SN Ia progenitors, is in the middle of the “final” region (Hachisu et al. 2000a, 2000b). The resultant explosions are “normal” SNe Ia.

A simple estimation gives the border between case CALM and case RN: $M_t = M_{\text{acc}}$ and $R_2 = R_2^*$ at the SN Ia explosion. Here we calculate $M_2$ from equation (17) and take $R_2$ and $L_2$ from Tout et al. (1997; a single-star evolution). These lines agree reasonably with the border of CALM-RN in Figures 6, 8, and 10.

For a typical case RN scenario with $M_{\text{w},0} = 1.0 M_\odot$, $M_{\text{w},0} = 2.0 M_\odot$, $P_0 = 1.18$ days, and $c_1 = 3$, the WD undergoes an SN Ia explosion in the recurrent nova phase at $t = 9.49 	imes 10^3$ yr after the secondary first fills its Roche lobe. The WD wind stops at $t = 4 	imes 10^3$ yr, and the stable hydrogen burning ends at $t = 8.6 	imes 10^3$ yr. During the last $10^3$ yr in the recurrent nova phase, the secondary loses $\sim 0.022 M_\odot$, of which the WD accretes $0.017 M_\odot$. Therefore, the amount of stripped-off matter in the recurrent nova phase is very small. On the other hand, the stripped-off matter in the early wind phase amounts to $\Delta M_{\text{strip}} \approx 0.15 M_\odot$, which is already far from the SN at the SN Ia explosion; i.e., $(10$–$100$ km s$^{-1})(5 \times 10^5$ yr) = $(1$–$10) \times 10^{19}$ cm. It takes about $100$–$1000$ yr for the SN ejecta to reach the stripped-off matter. These features are summarized in Table 1.

### 5. DISCUSSION

#### 5.1. Mass-stripping Effect and Modulated Mass Transfer Rate

As mentioned in § 1, the existence of the mass-stripping effect has been demonstrated by Hachisu & Kato (2003b, 2003c). They analyzed two quasi-periodic transient supersoft X-ray sources, RX J0513.9–6951 in the Large Magellanic Cloud (LMC), and V Sge in our Galaxy. In particular, V Sge shows the following key observational features. (1) V Sge exhibits long-term transitions between optical high (brightness of $V \sim 11$ and duration of $\sim 180$ days) and low ($V \sim 12$ and $\sim 120$ days) states with total durations of $\sim 300$ days (see, e.g., Simon & Mattei [1999] for the long-term behavior). (2) Very soft but very weak X-rays are detected only in the long-term optical low state (e.g., Greiner & van Teeseling 1998). (3) Radio observations indicate a wind mass-loss rate as large as $\sim 10^{-5} M_\odot$ yr$^{-1}$ (Lockley et al. 1997, 1999).

Hachisu & Kato (2003c) explained these features on the basis of the mass-stripping effect: the mass transfer to the WD is modulated by the WD wind because mass stripping attenuates the mass transfer rate. This interaction leads to high and low states. The mass-loss rate of the WD wind (with a high velocity of $\gtrsim 1000$ km s$^{-1}$) reaches as high as $M_{\text{wind}} \sim 1 \times 10^{-5} M_\odot$ yr$^{-1}$, which is consistent with radio observations. Thus, the mass transfer rate itself may not be constant but may vary in time,

| WD Mass $(M_\odot)$ | Secondary Mass $(M_\odot)$ | Orbital Period (days) | Case | Pre-SN History | SN Ia |
|------------------|-----------------|-------------------|------|---------------|-------|
| 1.0–1.1………. | 3–6 | $\sim 0.5$–2 | WIND | WIND—SSXS | Normal Ia |
| 3–6 | $\sim 2$–10 | CALM | WIND—SSXS | Normal Ia |
| 2.2–3 | $\sim 0.5$–4 | CALM | WIND—SSXS | Normal Ia |
| 1.8–2.2 | $\sim 0.5$–2 | RN | WIND—SSXS—RN or SSXS—RN | Normal Ia |
| 0.9………. | 2.5–5 | $\sim 0.5$–6 | CALM | WIND—SSXS | Normal Ia |
| 2.0–2.5 | $\sim 0.5$–2 | RN | WIND—SSXS—RN | Normal Ia |
| 0.8………. | 4–5 | $\sim 1$–3 | RN | WIND—SSXS—RN | Normal Ia |
| 4–5 | $\sim 0.5$–1 | CALM | WIND—SSXS | Normal Ia |
| 2.5–4 | $\sim 0.5$–2 | RN | WIND—SSXS—RN | Normal Ia |
| 0.7………. | 3–4.5 | $\sim 0.5$–1 | RN | WIND—SSXS—RN | Normal Ia |

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**TABLE 2**

**INITIAL PARAMETERS FOR THREE SN Ia EXPLOSIONS**
which is why it is regarded as a time-averaged rate in the present paper.

From the light-curve fitting, Hachisu & Kato (2003c) also estimated the WD mass as $M_{\text{WD}} \sim 1.25 M_\odot$ and the secondary mass as $M_{\text{MS}} \sim 3.5 M_\odot$, and they concluded that V Sge will explode as an SN Ia on a timescale of $\sim 1 \times 10^5$ yr. Since the present orbital period of V Sge is 0.51 days (Herbig et al. 1965; Patterson et al. 1998), its position in the orbital period–donor mass plane in Figure 3 indicates a value of $c_1 > 0$. Thus, we may regard binaries that are in the wind phase as ‘‘V Sge–type stars.”

5.2. Paucity of Progenitor Systems

The lifetime of V Sge–type stars is typically a few to several times $10^5$ yr, mainly because the time-averaged mass-stripping rate is as high as $M_{\text{MS}} \sim 10^{-3} M_\odot \text{yr}^{-1}$. If this channel of the WD + MS system produces about four Type Ia supernovae per millennium in our Galaxy (e.g., Cappellaro et al. 1999), we should have a chance to observe at least several hundred V Sge–type stars in our Galaxy. Steiner & Diaz (1998) listed four V Sge–type stars in our Galaxy and discussed their similar properties. Although the masses of the companion stars to the WDs have not yet been clearly identified, their orbital periods fall in the range of 0.2–0.5 days, which is very consistent with the orbital periods predicted by our new scenario (see the “final” regions in Figs. 5–10). However, the total number of V Sge–type stars is too small (by about 2 orders of magnitude) to be compatible with the new scenario, unless 99% of V Sge–type stars are hidden.

The same kind of paucity of the progenitors has been already pointed out for supersoft X-ray sources in our Galaxy and has been attributed to the Galactic interstellar absorption of supersoft X-rays (Di Stefano & Rappaport 1994). Di Stefano & Rappaport also suggested that circumstellar matter may play some role in the obscuration of X-rays.

Diaz & Steiner (1995) pointed out that the soft X-ray flux of V Sge is too weak to be compatible with those of the typical supersoft X-ray sources; i.e., at least 2 or 3 orders of magnitude lower than that of CAL 87, a prototypical SSXS in the LMC. This obscuration may be explained with the absorption of X-rays by the stripped matter (or the WD wind itself) and may also be related to the observational paucity of the supersoft X-ray sources.

As is mentioned in §1, Di Stefano & Kong (2003) reported the number of SSXSs in four external galaxies from Chandra data. They have estimated at least several hundred SSXSs in each galaxy, many of which are obscured by interstellar absorption.

5.3. Angular Momentum Loss by Stripped Matter

Some angular momentum is lost from the binary system along with the stripped matter. In our treatment, we assume that the specific angular momentum (angular momentum per unit mass) of the stripped matter is given by equation (6); that is, that the ablated gas from the companion has the specific angular momentum as that at the companion’s surface. This assumption may be too simplified, because the stripped matter may pick up some angular momentum from the binary motion during its journey. Here we examine other two cases: one is the same as the high-velocity WD wind, i.e.,

$$ l_s = \left( \frac{1}{1 + q} \right)^2, $$

(19)

and the other is the low-velocity case, i.e.,

$$ l_s = 1, $$

(20)

where the stripped matter picks up a large amount of angular momentum from the binary torque (see Jahanara et al. [2005] for a recent three-dimensional hydrodynamic calculation).

For the first case, that of equation (19), we have obtained essentially the same results as in equation (6). If we adopt the second case, that of equation (20), however, we have common envelope formations in a hundred or a thousand years for $c_1 = 3$, $M_{\text{MS}} = 5.0 M_\odot$, and $M_{\text{WD},0} = 1.0 M_\odot$ in Figure 7 regardless of the value of $P_0$. If we start the evolution with $c_1 = 3$, $M_{\text{MS}} = 4.0 M_\odot$, and $M_{\text{WD},0} = 1.0 M_\odot$, we obtain SN Ia explosions only for $P_0 = 2$–5 days. These results hardly change even if we increase the efficiency of the mass-stripping effect to $c_1 = 10$. This is because too much angular momentum is removed from the binary for the case using equation (20), and this makes the separation shrink drastically regardless of the value of $c_1$. Evolutions with $c_1 = 3$, $M_{\text{MS}} = 3.5 M_\odot$, and $M_{\text{WD},0} = 1.0 M_\odot$ result in the same final outcome as in equation (6).

On the other hand, there are four V Sge–type stars with short orbital periods of 0.2–0.5 days (Steiner & Diaz 1998). Therefore, we conclude that the angular momentum loss is much closer to that in equations (6) or (19) rather than that in equation (20), because these V Sge–type stars cannot be realized with the large angular momentum loss as in equation (20) that results in the formation of a common envelope.

5.4. Mass Transfer Rate of the Simplified Treatment

Our treatment of thermal timescale mass transfer may be too simplified compared with the detailed mass transfer model studied by Langer et al. (2000) and Han & Podsiałowski (2004). Han & Podsiałowski compared our results based on a simplified model (Hachisu et al. 1999b) with their detailed model calculations, and they pointed out that the difference is large for lower mass WDs. Although we need a detailed mass transfer model in order to obtain precise SN Ia parameters, our treatment has the advantage of easy and simple estimation for the SN Ia parameter region. As pointed out by Han & Podsiałowski (2004), our SN Ia region thus calculated may deviate from the realistic one for less massive WDs. However, our SN Ia region is probably not so very different from the realistic one for more massive WDs (compare with Fig. 12 of Hachisu et al. [1999b] and Figs. 3 and 5 of Han & Podsiałowski [2004]).

6. CONCLUDING REMARKS

Both cases WIND and CALM originate from the systems with massive donors; i.e., a young population. It will be important to make some comparisons with the observational data, such as frequency and population. The red hatched regions in Figures 5, 7, and 9 indicate a region in which the progenitor explodes at $t_{\text{delay}} \leq 100$ Myr. Also, the dashed lines and the dotted lines correspond to values of $t_{\text{delay}} = 200$ and 400 Myr, respectively. We see in Figure 11 that case WIND and thus SNe Ia/Iln (IIa) are realized by very young systems with $t_{\text{delay}} \leq 100$–200 Myr.

If $M_{\text{WD},0} \lesssim 0.9 M_\odot$, we have almost no region for case WIND, which is different from the cases with $M_{\text{WD},0} \gtrsim 1.0 M_\odot$. If all the WD + MS systems with $M_{\text{MS}} \gtrsim 3$–6 $M_\odot$ ($c_1 = 3$), $M_{\text{WD},0} \gtrsim 1.0 M_\odot$ ($M_{\text{MS}} \gtrsim 6.5 M_\odot$), and $P_0 \sim 0.5$–2 days produce SNe Ia/In (IIa) events (Table 2), the frequency of these events is estimated to be $\sim 5\%$ (including both the WD + MS and WD + RG systems, with a total number ratio for these systems of 4:2).
A group of Type IIn SNe such as SN 1997cy and SN 1999E shows very similar spectroscopic and photometric features to those of SN 2002ic (Wang et al. 2004; Deng et al. 2004; Prieto et al. 2007). If these are in fact all Type Ia/IIn (Ia) SNe, their frequency can be estimated to be $\sim 1\times 10^{-4}$% (Prieto et al. 2007), which is consistent with the above estimate.

Type Ia supernovae play a key role in astrophysics, and thus our progenitor model has important implications. Our model depends essentially on the parameter of the stripping effect, $c_1$, which depends on the properties of WD winds, such as asphericity, velocities, and the efficiency of energy conversion. Also, we calculate the mass transfer rate using the simple approximate binary models. In order to improve these parameterizations and approximations, we will need multidimensional hydrodynamical simulations, which are beyond the scope of the present study. In the present approach, we constrain the $c_1$ parameter observationally and estimate values of $c_1 \sim 7\sim 8$ and $c_1 \sim 5\sim 10$ from the analysis of V Sge and RX J0513.9–6951, respectively. Keeping in mind the necessity of further theoretical and observational studies to confirm our new progenitor systems, we summarize the basic results of our new SN Ia scenario:

1. Mass-accreting WDs blow an optically thick wind when the mass transfer rate to the WD exceeds the critical rate of $M_{\text{cr}} \sim 1 \times 10^{-6} M_\odot \text{yr}^{-1}$. The WD wind collides with the secondary’s surface and strips off its surface. If the mass-stripping effect is efficient enough, the mass transfer rate to the WD is attenuated and the binary can avoid forming a common envelope, even for a rather massive secondary. By including this mass-stripping effect in our binary evolution model of the WD + MS systems, we have found a new evolutionary scenario, in which a companion as massive as $6\sim 7 M_\odot$ can produce an SN Ia for a reasonable strength of the mass-stripping effect, say, $c_1 \sim 3$.

2. We have followed simplified binary evolutions and obtained the SN Ia region in the $\log P_0$–$M_{2,0}$ (initial orbital period–initial donor mass) plane. The newly obtained SN Ia region extends to massive donor masses of up to $M_{2,0} \sim 6\sim 7 M_\odot$ for $P_0 \sim 0\sim 10$ days, although the extension depends on the strength of the mass-stripping effect, $c_1$; i.e., $M_{2,0} \sim 7\sim 8 M_\odot$ for $c_1 = 10$, $M_{2,0} \sim 5\sim 6 M_\odot$ for $c_1 = 3$, and $M_{2,0} \sim 4 M_\odot$ for $c_1 = 1$.

3. We have estimated that the SN Ia birthrate in our Galaxy is $\dot{N}_{\text{SN Ia}} \sim 0.004 \text{ yr}^{-1}$ (for $c_1 = 3$), which is consistent with observations. The rates of young populations, i.e., $\dot{N}_{\text{delay}} \lesssim 100 \text{ Myr}$ and $\dot{N}_{\text{delay}} \lesssim 200 \text{ Myr}$, are about 50% and 80% of the total SN Ia rate of the WD + MS channel. These short delay times of SN Ia progenitors are consistent with the recent observational suggestions that half of SNe Ia belong to such a very young population as would have a delay time of $\dot{N}_{\text{delay}} \sim 10^3 \text{ yr}$.

4. Another channel of the WD + RG system shows a broad distribution of the delay time over 2–3 Gyr (Hachisu et al. 1999a); thus, the two (WD + MS and WD + RG) channels yield a bimodal delay time distribution.

5. The stripped-off material is probably distributed on the orbital plane and forms a massive circumbinary torus (or disk) around SNe Ia. Such circumstellar matter may be consistent with the observed CSM feature in SN 2006X. When SN ejecta strongly interact with a massive CSM, it can explain the feature of the Type Ia/IIn (Ia) supernovae SN 2002ic and SN 2005gj.

6. Three different environments of SN Ia explosions can be specified by three different states of WDs just at the SN Ia explosion: i.e., the optically thick WD wind phase (case WIND), the steady hydrogen-burning phase without optically thick winds from WDs (case CALM), and the recurrent nova phase (case RN). In case WIND, SN Ia ejecta strongly interact with a massive CSM, such as in the Type Ia/IIn (Ia) supernovae SN 2002ic and SN 2005gj, because CSM exists near the SN Ia. The estimated rate of case WIND is $\sim 5\%$ of the total SN Ia rate, which is consistent with the observational estimate. In cases CALM and RN, SNe show a normal SN Ia feature because the CSM is far from the SN, but the ejecta may interact with the CSM in a much later phase. SN 2006X may be on a border between case WIND and case CALM.

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