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A NEW MODEL FOR PROGENITOR SYSTEMS OF TYPE Ia SUPERNOVAE

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ABSTRACT

We propose a new model for progenitor systems of Type Ia supernovae. The model consists of an accreting white dwarf and a lobe-filling, low-mass red giant. When the mass accretion rate exceeds a certain critical rate, there is no static envelope solution on the white dwarf. For this case, we find a new strong wind solution, which replaces the static envelope solution. Even if the mass-losing star has a deep convective envelope, the strong wind stabilizes the mass transfer until the mass ratio, q, between the mass-losing star and the mass-accreting white dwarf reaches 1.15, i.e., $q < 1.15$. A part of the transferred matter can be accumulated on the white dwarf at a rate that is limited to $\dot{M}_{\rm cr} = 9.0 \times 10^{-7}\ (M_{\rm WD}/M_\odot - 0.50)\ M_\odot\ {\rm yr}^{-1}$, and the rest is blown off in the wind. The photospheric temperature is kept around $T \sim 1 \times 10^5$–2×10^5 K during the wind phase. After the wind stops, the temperature quickly increases up to $\sim 1 \times 10^6$ K. The white dwarf steadily burns hydrogen and accretes helium, thereby being able to increase its mass up to 1.38 $M_\odot$ and explode as a Type Ia supernova. The expected birth rate of this type of supernovae is consistent with the observed rate of Type Ia supernovae.

The hot white dwarf may not be observed during the strong wind phase due to self-absorption by the wind itself. The Strong wind stops when the mass transfer rate decreases below $\dot{M}_{\rm cr}$. Then it can be observed as a supersoft X-ray source.

Subject headings: binaries: close — binaries: symbiotic — stars: mass-loss — stars: novae, cataclysmic variables — supernovae: general — X-rays: stars

1. INTRODUCTION

Observations and models strongly indicate that Type Ia supernovae (SNs Ia) are thermonuclear explosions of accreting white dwarfs (WD). Theoretically, both the Chandrasekhar mass white dwarf models (Ch) and the sub-Chandrasekhar mass models (sub-Ch) have been considered (e.g., Woosley 1990; Nomoto et al. 1994; Nomoto et al. 1996; for recent reviews, Branch et al. 1995). Though these white dwarf models can more or less account for various observational aspects of SNs Ia, the exact binary evolution that leads to SNs Ia has not been identified. Different evolutionary scenarios have been proposed, but neither of them has been positively proved yet. They include the following: (1) a double degenerate scenario (DD), i.e., the merging of double C + O white dwarfs with a combined mass surpassing the Ch mass limit (e.g., Iben & Tutukov 1984; Webbink 1984); and (2) a single degenerate scenario (SD), i.e., accretion of hydrogen via mass transfer from a binary companion at a relatively high rate (e.g., Nomoto 1982). Currently, the issues of Ch versus sub-Ch and DD versus SD are still debated (e.g., Branch et al. 1995 for a review).

Among the possible combinations, the DD/Ch scenario has not been well supported. Observationally, the search for the DD has revealed only a few systems whose combined mass is less than the Ch mass (Branch et al. 1995; Renzini 1996 for reviews). Theoretically, the DD has been suggested to lead to accretion-induced collapse (AIC) rather than SNs Ia (Nomoto & Iben 1985; Saio & Nomoto 1985).

For the SD scenario, possible observed systems may be symbiotic stars (e.g., Munari & Renzini 1992). Kenyon et al. (1993) have suggested that symbiotics are more likely to lead to the sub-Chandrasekhar mass explosion because the available mass in transfer may not be enough for white dwarfs to reach the Chandrasekhar mass. Renzini (1996) has therefore concluded that the SD/sub-Ch combination scores better than the SD/Ch and DD/Ch combinations.

However, photometric and spectroscopic features of SNs Ia are better reproduced by the Chandrasekhar model than the sub-Chandrasekhar model (e.g., Nomoto et al. 1994; Nomoto et al. 1996; Branch et al. 1995; Höflich & Khokhlov 1996). Here we shed new light on the SD/Ch scenario, and we propose a new progenitor model for SNs Ia. Our scenario may also account for why the number of the observed DD is significantly less than the predictions by Iben & Tutukov (1984) and Webbink (1984).

In the scenario of Iben & Tutukov (1984) and Webbink (1984), they excluded a close binary system consisting of a mass-accreting WD and a lobe-filling red(sub-) giant (RG), mainly because such a system suffers from unstable mass transfer when the mass ratio of the mass-accreting WD to the mass-losing RG exceeds 0.79, i.e., $q > 0.79$. However, the advent of new opacities may change all of these pictures because a strong peak in the opacity has been reported at the temperature $\log T({\rm K}) \sim 5.2$ (Iglesias, Rogers, & Wilson 1987, 1990; Iglesias & Rogers 1991, 1993; Rogers & Iglesias 1992). This peak in the new opacity is about 3 times larger than that

1996ApJ...470L..97H

of the Los Alamos opacity (Cox & Stewart 1970a, 1970b; Cox, King & Tabor 1973). Such a large enhancement of the new opacity certainly drives a strong wind on the mass-accreting WD because the acceleration of envelope matter is directly affected by the opacity value, especially when the luminosity is very close to the Eddington luminosity, as seen in nova envelopes (Kato & Iben 1992; Kato & Hachisu 1994). If this is the case, strong winds from the mass-accreting white dwarf change the stability condition up to $q < 1.15$ and are able to open a channel to a Type Ia supernova explosion.

2. PROGENITOR MODEL

We assume that the progenitor of Type Ia supernovae is a close binary system consisting initially of a C + O white dwarf with $M_{\mathrm{WD},0} = 0.8\text{–}1.2\ M_\odot$ and a low-mass red(sub) giant star with $M_{\mathrm{RG},0} = 0.8\text{–}1.5\ M_\odot$, and having a helium core of mass $M_{\mathrm{He}} = 0.2\text{–}0.4\ M_\odot$. This assumption is consistent with the fact that SNs Ia appear everywhere in spiral galaxies and even in elliptical galaxies (e.g., Tammann 1982; Cappellaro & Turatto 1988). We have followed the binary evolution of these systems by using empirical formulae, and we obtained the parameter range that can produce an SN Ia.

When the low-mass companion evolves to a red (sub) giant and fills its inner critical Roche lobe, mass transfer begins from the RG to the WD. If a steady mass transfer is realized, its rate is given by

$$\frac{\dot{M}_2}{M_2} = \left(\frac{\dot{R}_2}{R_2}\right)_{\mathrm{EV}} \bigg/ H(q), \tag{1}$$

where $(\dot{R}_2/R_2)_{\mathrm{EV}}$ represents specifically the evolutionary change in the secondary radius, and

$$H(q) = \frac{d \ln f(q)}{d \ln q}(1 + q) - 2(1 - q), \tag{2}$$

where q is the mass ratio, $q \equiv M_2/M_1$ (M_1 is the mass of the primary, i.e., the C + O WD component, and M_2 the mass of the secondary, i.e., the low-mass RG component). Here we use the empirical formula proposed by Eggleton (1983), i.e.,

$$\frac{R_1^*}{a} = f(q) = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \tag{3}$$

as an effective radius (R_1^*) of the inner critical Roche lobe. Here, a is the separation, and we simply assume a circular orbit. To estimate $(\dot{R}_2/R_2)_{\mathrm{EV}}$, we use the empirical formulae proposed by Webbink, Rappaport, & Savonije (1983). We have used the same parameters as Webbink et al. (1983) for Population I stars.

For a sufficiently large mass of the secondary M_2 (i.e., $q > 0.79$), however, equation (1) gives a positive value of $\dot{M}_2$. This means that the mass transfer proceeds not on an evolutionary timescale but rather on a thermal or dynamical timescale. The gas falls very rapidly onto the WD and forms an extended envelope around the WD (e.g., Nomoto, Nariai, & Sugimoto 1979; Iben 1988). This envelope expands to eventually fill the inner and then outer critical Roche lobe. This results in the formation of a common envelope, in which the two cores are spiraling in each other. The envelope forms a very compact binary system consisting of a C + O WD and a helium WD, and it never produces an SN Ia.

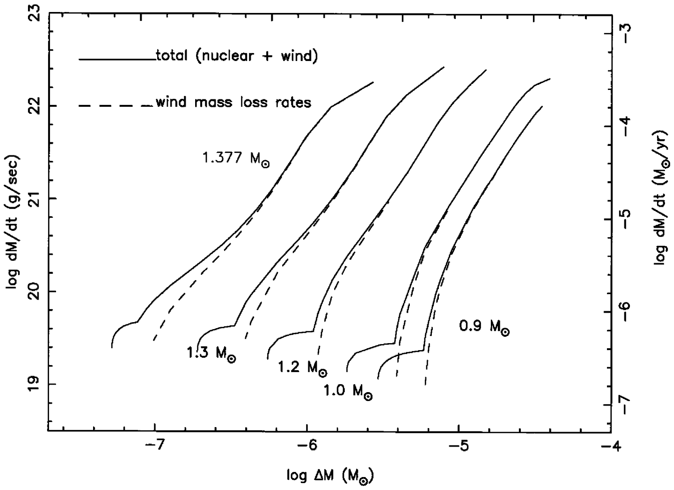

FIG. 1.—Wind mass-loss rate (*dashed line*) and total mass consumption rate (*solid line*); i.e., nuclear burning rate plus wind mass-loss rate are plotted against the envelope mass for WDs with masses of 0.9, 1.0, 1.2, 1.3, and 1.377 $M_\odot$. Mass is attached to each line.

However, the recent version of the opacity changes the situation; it drives an optically thick wind. Optically thick wind is a continuum-radiation driven wind in which the acceleration occurs deep inside the photosphere (e.g., Kato & Hachisu 1994). We have shown such solutions in Figure 1 for a solar composition ($X = 0.70$, $Y = 0.28$, $Z = 0.02$ for hydrogen, helium, and heavy element in weight, respectively). Wind mass-loss rates (*dashed lines*) are plotted against the envelope mass. A part of the transferred matter is blown off by the wind and the rest is accreted onto the WD after it burns into helium. The total mass consumption rate (nuclear burning plus wind mass loss; *solid line*) is also plotted in the same figure. Here we assume steady state and spherical symmetry to calculate structures of mass-losing envelopes. It is an important but not yet justified assumption that the WD accretes matter from the equator and blows wind from the other area. This assumption may be supported by a relatively similar example of SS 433—a system of the super Eddington accretion and jets—in which the mass accretor is not a WD but may be a neutron star. Possibilities of wind plus accretion on white dwarfs have never been discussed by Greggio & Renzini (1990) and Eggleton (1996, private communication).

The wind velocity is about several hundred to 1000 km s^{-1} when the mass transfer rate is $\lesssim 1 \times 10^{-5}\ M_\odot$ yr^{-1}; in other words, the wind velocity is about 10 times faster than the orbital velocity. For such a case, the wind has the same specific angular momentum as that of the WD, which is estimated as

$$\frac{\dot{J}}{\dot{M}} = \ell a^2 \Omega_{\mathrm{orb}}, \tag{4}$$

where the numerical factor is given by $\ell = [q/(1 + q)]^2$, J is the total angular momentum, M is the total mass of the system, and Ω_{orb} is the orbital angular velocity. The wind carries angular momentum, thereby reducing the orbital separation. In this sense, wind helps to destabilize the mass transfer. On the other hand, wind decreases the total mass of the binary so that it increases the orbital separation, and this effect stabilizes the mass transfer. Which of these effects wins determines the stability of mass transfer. These effects of mass transfer can be expressed as

$$\frac{\dot{M}_2}{M_2} = \left[\left(\frac{\dot{R}_2}{R_2}\right)_{\mathrm{EV}} - H_1(q)\left(\frac{\dot{M}_1}{M_1}\right)\right] \bigg/ H_2(q), \tag{5}$$

1996ApJ...470L..97H

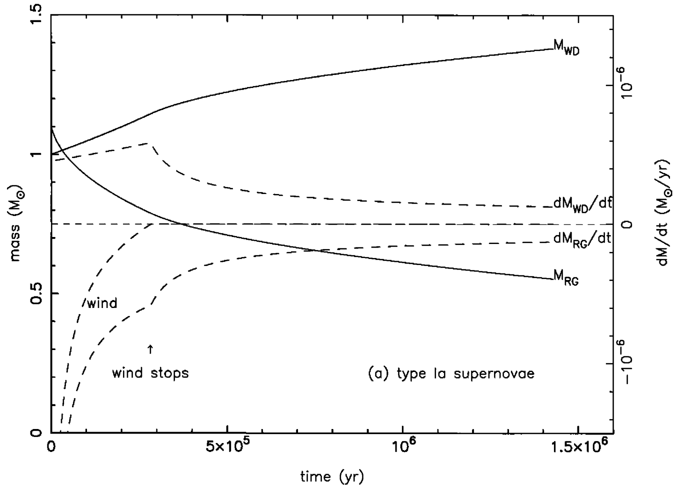

FIG. 2.—Time evolution of the system. WD increases its mass through 1.38 $M_\odot$ and explodes as an SN Ia. Solid lines denote the masses of the WD and the red giant companion. Dashed lines denote the net mass accumulation rate onto the white dwarf, the wind mass-loss rate, and the mass transfer rate from the red giant companion, respectively, from top to bottom.

$$H_1(q) = -\frac{d\ln f(q)}{d\ln q} + \frac{1}{1+q} - 2 + 2\ell\frac{1+q}{q}, \quad (6)$$

$$H_2(q) = \frac{d\ln f(q)}{d\ln q} + \frac{q}{1+q} - 2 + 2\ell(1+q). \quad (7)$$

Function $H_2(q)$ changes its sign at $q = 1.15$ for $\ell = (q/(1+q))^2$. Wind mass loss can stabilize the mass transfer from $q = 0.79$ to $q = 1.15$. It should be noted that small specific angular momentum of the wind, such as $\ell = [q/(1+q)]^2 \sim 0.25$ for $q \sim 1$, is essential to stabilize the mass transfer.

The WD can accrete the processed matter at a rate of

$$\dot{M}_{\rm cr} = 9.0\times10^{-7}\left(\frac{M_{\rm WD}}{M_\odot} - 0.50\right) M_\odot\ {\rm yr}^{-1} \quad (8)$$

during the strong wind phase, as shown in Figure 1. When the mass transfer rate decreases below this critical value, optically thick wind stops. If the mass transfer rate decreases further below $\sim1.0\times10^{-7}$ $M_\odot$ yr^{-1}, hydrogen shell burning becomes unstable and triggers a weak shell flash. In this paper, we assume that the WD can accrete all of the transferred matter until the mass transfer rate decreases below 0.5×10^{-7} $M_\odot$ yr^{-1}.

The system can be specified by three parameters: initial WD mass, $M_{\rm WD,0}$, the initial red giant mass, $M_{\rm RG,0}$, and the mass of the helium core of the red giant at the beginning of mass transfer, $M_{\rm RG,0}$(He) (or the separation of the binary, q_0). We have followed the evolution of these close binary systems for various sets of parameters. If the mass transfer rate becomes smaller than 0.5×10^{-7} $M_\odot$ yr^{-1} before the WD reaches 1.38 $M_\odot$, then we note that hydrogen shell flashes on the WD blow off the accumulated matter and the WD never grows any more. We assume that all of the transferred matter can be processed and then accumulated on the WD when the mass transfer rate is larger than 0.5×10^{-7} $M_\odot$ yr^{-1}.

An example of such evolutions ($M_{\rm WD,0} = 1.0\,M_\odot$, $M_{\rm RG,0} = 1.1$ $M_\odot$, $M_{\rm RG,0}$(He) = 0.40 $M_\odot$) is plotted in Figure 2. In this case, the WD can grow up to 1.38 $M_\odot$ to trigger an SN Ia. At the beginning, the mass transfer rate is as large as several times 10^{-6} $M_\odot$ yr^{-1} so that almost all of the transferred matter is blown off by the wind. The mass transfer rate decreases quickly to below $\dot{M}_{\rm cr}$, so that the strong wind stops 3×10^5 yr after the beginning of mass transfer. The WD accretes only 0.15 $M_\odot$ during this strong wind phase. After the wind stops, the mass transfer rate can be determined by equation (1). The mass transfer rate is gradually decreasing from 6×10^{-7} $M_\odot$ yr^{-1} to 2×10^{-7} $M_\odot$ yr^{-1} just before the SN Ia explosion of the WD. The photospheric temperature stays around $2\text{–}3\times10^5$ K during the strong wind phase, but then it quickly increases up to 1×10^6 K just after the wind stops. This phase lasts for 1×10^6 yr until the supernova explosion. At the time of the explosion, the mass of the hydrogen envelope on the white dwarf is $<10^{-6}$ $M_\odot$ (Fig. 1), which is too small to be observed. On the other hand, there still remains $\sim$0.1 $M_\odot$ of hydrogen in the red giant envelope, and it may be observed as low-velocity components of the Hα line.

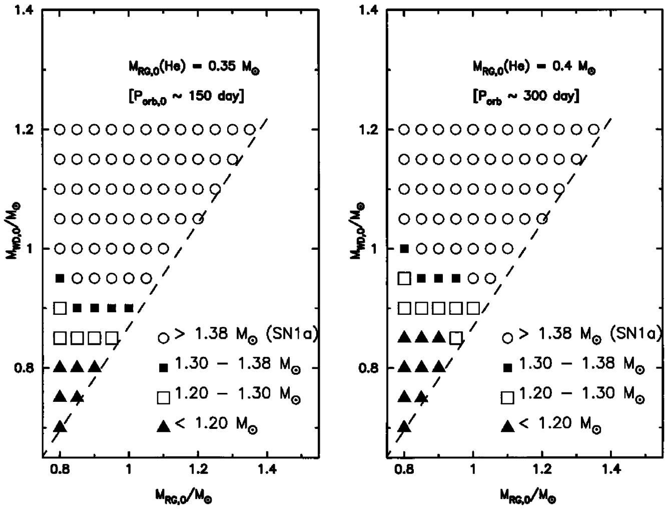

FIG. 3.—Outcome of the evolution as a function of the initial white dwarf mass, the initial red giant mass, and the mass of helium core at the beginning of mass transfer.

The final outcome of the evolution is summarized in Figure 3 against these three parameters. We have stopped the evolution when the WD mass reaches 1.38 $M_\odot$, when the mass transfer rate becomes less than 0.5×10^{-7} $M_\odot$ yr^{-1}, or when the helium core mass reaches 0.46 $M_\odot$. The mass of the WD at the end of the evolution is shown in the Figure 3. We have examined four cases of the mass of the helium core at the beginning of mass transfer—$M_{\rm RG,0}$(He) = 0.25, 0.30, 0.35, and 0.40 $M_\odot$—but we have shown only two cases in the figure. We maintain that the initial mass of the WD should be more massive than 0.9 $M_\odot$ for $M_{\rm RG,0}$(He) $\sim$ 0.40 $M_\odot$ (the orbital period, $P_{\rm orb,0}$ $\sim$ 300 days) and for $M_{\rm RG,0}$(He) $\sim$ 0.35 $M_\odot$ ($P_{\rm orb,0}$ $\sim$ 150 days). On the other hand, $M_{\rm WD,0} > 1.05$ $M_\odot$ is required for the case of $M_{\rm RG,0}$(He) $\sim$ 0.30 $M_\odot$ ($P_{\rm orb,0}$ $\sim$ 60 days), and $M_{\rm WD,0} > 1.15$ $M_\odot$ is required for $M_{\rm RG,0}$(He) $\sim$ 0.25 $M_\odot$ ($P_{\rm orb,0}$ $\sim$ 20 days). Thus, the region to induce an SN Ia is much smaller for $M_{\rm RG,0}$(He) $\lesssim 0.30$ $M_\odot$ than for $M_{\rm RG,0}$(He) $\gtrsim 0.35$ $M_\odot$.

3. DISCUSSIONS

The steady hydrogen shell burning converts hydrogen into helium on top of the C + O core and increases the mass of

1996ApJ...470L..97H

the helium layer gradually. When its mass reaches a certain value, helium ignites. For the accretion rate given by equation (8), helium shell burning is unstable and a flash grows. Once a helium shell flash occurs on relatively massive white dwarfs ($M_{\rm WD} \gtrsim 1.2\,M_\odot$), a part of the envelope mass is blown off by the wind (Kato, Saio, & Hachisu 1989); however, the ratio of the lost mass to the initial envelope mass is very small (less than several percent). The total mass lost from the system would be smaller than 0.01 $M_\odot$ during the strong wind phase.

After the wind stops, the mass transfer rate is gradually decreasing to $\sim 2 \times 10^{-7}\,M_\odot\ {\rm yr}^{-1}$, as shown in Figure 2. The smaller the mass accretion rate, the stronger the helium shell flush. In this sense, it is expected that much more mass will be blown off by the wind during the helium shell flush. On the other hand, the gravitational potential on the WD surface becomes so deep that the WD mass increases to the Chandrasekhar limit. The nuclear energy per unit mass of the burning helium is almost the same as the potential energy for such massive WDs as $\sim 1.3\,M_\odot$. Therefore, we expect no severe loss of the envelope mass, although it should be recalculated with the new opacity.

The effective temperature of the accreting WD is ~ 1–3×10^5 K during the strong wind phase. The hot component of the progenitor may not be observed due to self-absorption by wind itself. Once the mass transfer rate decreases below the critical value given by equation (8), wind stops and the photospheric temperature quickly increases up to $\sim 1 \times 10^6$ K, because the photospheric temperature depends greatly on the mass transfer rate when the envelope is static. The hot component may be observed as a supersoft X-ray source.

If we assume that 5–8 $M_\odot$ stars leave C + O WDs more massive than 0.9 $M_\odot$ stars (e.g., Weidemann & Koester 1983; Iben & Tutukov 1985), then the rate of SNs Ia coming through this route is close to the observed rate—i.e., 0.002 ${\rm yr}^{-1}$ in our Galaxy. Here we have estimated the rate by using equation (1) of Iben & Tutukov (1984) and substituting $\Delta \log A = 2$, $q = 0.1$–0.3, $M_A = 8$, and $M_B = 5$.

It has been pointed out that the number of the observed DD is significantly less than the predictions by Iben & Tutukov (1984) and Webbink (1984). Our scenario suggests that the binary system can avoid the formation of a common envelope even for the unstable mass transfer (i.e., $q > 1.15$ in case A and early case B mass transfer) if the mass transfer rate does not exceed much more than $\sim 10^{-4}\,M_\odot\ {\rm yr}^{-1}$. For such a rate, the transferred matter would be blown off in wind as shown in Figure 1. The mass transfer rate itself is determined by the thermal timescale of the envelope and lies between $1 \times 10^{-7}\,M_\odot\ {\rm yr}^{-1}$ and $1 \times 10^{-6}\,M_\odot\ {\rm yr}^{-1}$ in the case A mass transfer of 2–3 $M_\odot$ star, or it is between $1 \times 10^{-6}\,M_\odot\ {\rm yr}^{-1}$ and $1 \times 10^{-4}\,M_\odot\ {\rm yr}^{-1}$ in the early case B mass transfer of a 2–3 $M_\odot$ star. If this is indeed the case, the rate of formation of very compact DDs should be reduced to much less than what is expected by Iben & Tutukov (1984) and Webbink (1984); then the discrepancy between the prediction and the observation of DDs may be resolved.

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