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Recurrent novae as progenitors of Type Ia supernovae

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Abstract. Recurrent novae are binaries harboring a very massive white dwarf (WD), as massive as the Chandrasekhar mass, because of their short recurrence periods of nova outbursts of 10–100 years. Thus, recurrent novae are considered as candidates of progenitors of Type Ia supernovae (SNe Ia). In fact, the SN Ia PTF 11kx showed evidence that its progenitor is a symbiotic recurrent nova. The binary parameters of recurrent novae have been well determined, especially for the ones with frequent outbursts, U Sco and RS Oph, which provide useful information on the elementary processes in binary evolution toward SNe Ia. Therefore we use them as testbeds for binary evolution models. For example, the original double degenerate (DD) scenario cannot reproduce RS Oph type recurrent novae, whereas the new single degenerate (SD) scenario proposed by Hachisu et al. (1999) naturally can. We review main differences between the SD and DD scenarios, especially for their basic processes of binary evolution. We also discuss observational support for each physical process. The original DD scenario is based on the physics in 1980s, whereas the SD scenario on more recent physics including the new opacity, mass-growth efficiency of WDs, and optically thick winds developed in nova outbursts.

Keywords : binaries: general – novae, cataclysmic variables – stars: mass-loss – white dwarfs – supernovae: general

1. Introduction

Nova outbursts are a thermonuclear runaway event on a white dwarf (WD). After the unstable hydrogen shell-burning sets in, the envelope greatly expands and the WD becomes very bright to reach optical maximum. Structures of such expanded envelopes are subject to the opacity that

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regulates the energy flux. In the beginning of 1990s opacity tables were revised by the OPAL (Iglesias, Rogers & Wilson 1987; Rogers & Iglesias 1992; Iglesias & Rogers 1996) and OP (Seaton et al. 1994) projects. These new opacities showed a prominent peak at a temperature of $\log T$ (K) ~ 5.2 due to iron lines, and brought drastic changes into stellar structures, especially when the luminosity is close to the Eddington luminosity. Using the new opacities, people solved many long-standing problems in pulsation, stellar evolution, and nova outbursts (e.g. Bressan et al. 1993; Schaller et al. 1992; Kato & Hachisu 1994; Prialnik & Kovetz 1995; Gautschy & Saio 1996, and references therein). Now a days the OPAL opacities are widely used in astronomy.

Nova theory has been greatly influenced by the new opacities. The strong peak in the opacity accelerates winds during nova outbursts and, as a result, timescales of nova outbursts are drastically shortened. With the old opacities (the Los Alamos opacities, e.g., Cox & Stewart 1970a,b; Cox & Tabor 1976), we had to assume that novae occur only in very massive WDs ($M_{\rm WD} \gtrsim 1.3\ M_\odot$) or that the frictional effect by a companion star to the WD is very effective in ejecting most of the WD envelope in a dynamical timescale. These assumptions were required for a relatively short duration of nova outbursts ($\sim$ 1 yr). With the new opacities, however, these assumptions are not needed anymore. In and after 1990 many numerical calculations were done with the OPAL opacities. We have now strong accelerations of winds that blow most of the envelope mass in a relatively short timescale of $\sim$ 1 yr. As a result, calculated nova timescales are drastically shortened (Kato & Hachisu 1994; Prialnik & Kovetz 1995). Kato developed an optically thick wind theory to follow the extended stage of nova outbursts and her group succeeded in reproducing nova light curves from slow to very fast novae (e.g., Hachisu & Kato 2006, 2010). Now we understood basic properties of novae, such as duration, expansion speed, multiwavelength properties, and light curves for all speed classes of novae.

Type Ia supernovae (SNe Ia) are characterized in principle by spectra with strong Si II but no hydrogen lines at maximum light. SNe Ia play very important roles in astrophysics as a standard candle for measuring cosmological distances and as main producers of iron group elements in chemical evolution of galaxies. It is commonly agreed that the exploding star is a mass-accreting carbon-oxygen (C+O) WD. For example, the SN Ia 2011fe indicates its size of the exploding star as small as $R < 0.02\ R_\odot$ (Bloom et al. 2012), consistent with its WD origin. However, it is not clarified yet whether the WD accretes H/He-rich matter from its binary companion (the so-called single degenerate (SD) scenario), or two C+O WDs merge, (the so-called double degenerate (DD) scenario) (e.g., Hillebrandt & Niemeyer 2000; Nomoto et al. 2000, for review). It was before the advent of the OPAL opacity that Webbink (1984) and Iben & Tutukov (1984) proposed the DD scenario. In this DD scenario, intermediate-mass (3–8 $M_\odot$) binaries undergo the first and second common envelope phases and finally become a double WD system with a very short orbital period of $\lesssim 3$ hr. They can merge within a Hubble time due to orbital energy and angular momentum losses by gravitational radiation. If the total mass of a merged object exceeds the Chandrasekhar mass, it could explode as an SN Ia. This is the traditional DD scenario.

Hachisu, Kato & Nomoto (1996) proposed a new idea, dubbed "accretion wind evolution," as a new elementary process in the binary evolution that leads to SN Ia explosions. This accretion wind evolution is based on the optically-thick nova wind theory, illustrated in Fig. 1. The WD

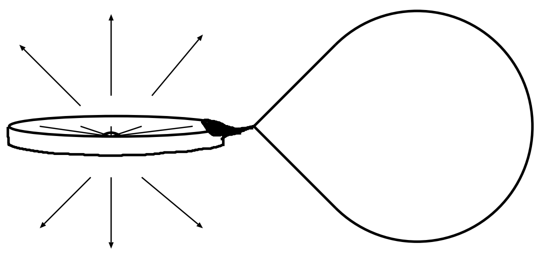

Figure 1. Accretion wind evolution in the SD scenario. Optically thick winds blow from a mass-accreting WD when the mass-transfer rate from its lobe-filling companion exceeds a critical rate, $\dot{M}_{\rm cr}$. Hydrogen steadily burns on the WD at the same rate of $\dot{M}_{\rm cr}$ (typically $\sim 1 \times 10^{-6}~M_\odot~{\rm yr}^{-1}$ in massive WDs), while transferred matter exceeding this burning rate is blown in the wind as shown in the figure.

accretes matter from the accretion disk and, at the same time, blows optically thick winds. The wind blows as far as the WD accretes matter from the equator at sufficiently high rates. In the accretion wind evolution, the strong and fast winds carry mass and angular momentum, so the mass transfer can be stabilized. This means that the so-called second common envelope evolution does not occur when the accretion wind evolution is realized. This changed the traditional binary evolution scenarios. Thus, Hachisu et al. (1996) established a new progenitor system of SNe Ia which consists of a mass-accreting WD and a red-giant (RG) donor star. In the accretion wind evolution, WDs can grow in mass and explode as an SN Ia. We call this the "accretion-wind single degenerate (awSD) scenario", if it is necessary to distinguish it from the old SD scenario first proposed by Whelan & Iben (1973).

Li & van den Heuvel (1997) adopted this idea as a fundamental process of binary evolution and found that, in some binaries, the second common envelope evolution does not occur and the WD can grow in mass up to the Chandrasekhar limit. These binaries consist mainly of a WD and a main-sequence (MS) star at the stage of mass transfer (WD+MS systems). This is also a new way that leads to SN Ia explosions and dubbed "MS channel." After that, Hachisu, Kato & Nomoto (1999a); Hachisu et al. (1999b) reformulated basic processes of binary evolution and found that the WD+RG systems (the so-called "symbiotic channel") contribute to the SN Ia rate as well as the WD+MS systems.

Recurrent novae are characterized by multiple recorded outbursts of novae. So far, ten objects were registered in our Galaxy as listed in Table 1. They should have a very massive WD close to the Chandrasekhar mass because of the short recurrence time of outbursts (e.g. Hachisu & Kato 2001b; Prialnik & Kovetz 1995, see also Fig. 2). The present evolutionary status of these recurrent novae can be well understood from the theoretical point of view, if we take into account the accretion wind evolution. The binary parameters of several recurrent novae locate just in the binary parameter regions of the MS and symbiotic channels of SNe Ia (e.g., Hachisu & Kato 2001b; Hachisu, Kato,& Nomoto 2012b, see also Fig. 3). Thus we use the binary parameters of recurrent novae as testbeds of scenarios on Type Ia supernova evolution.

In the original DD scenario proposed by Webbink (1984) and Iben & Tutukov (1984), the accretion wind evolution was not included, so the binary could evolve to a pair of WDs after the second common envelope evolution. Thus, the first essential difference between the SD and DD scenarios is in the accretion wind evolution, which was based on the optically thick wind theory that was developed after the new opacities appeared in 1990s. In the DD scenario, binaries undergo the second common envelope evolution and the evolutionary path is essentially governed by the parameters of common envelope evolution (e.g., Webbink 2008). The DD scenario is also based on other different assumptions from the SD scenario, some of which are based on 1980's physics. In the present review, we critically examine these assumptions in light of observations of recurrent novae and other related objects.

Section 2 introduces observational properties of Galactic recurrent novae. Section 3 summarizes our theoretical understanding of novae, especially some issues closely related to SN Ia progenitors, i.e., stability of accreting WDs and how to determine the WD mass. Section 4 shows that these recurrent novae locate at the final stage of evolutionary path to SNe Ia in the SD scenario. Section 5 examines several elementary processes that are important in binary evolution. Section 6 deals with some objects closely related to the SN Ia progenitor scenarios.

2. Recurrent novae: observations

Recurrent novae are a small subgroup of novae that have multiple recorded outbursts. Their characteristic properties are summarized as follows.

1. Recurrence periods between outbursts are as short as $\sim$ 10–100 yrs.
2. Optical light curves show a rapid decline.
3. Optical light curves often show a mid-plateau phase.
4. In the later phase of outbursts, it often becomes a transient supersoft X-ray source (SSS). This SSS period almost overlaps with the mid-plateau phase.
5. No heavy element enhancement is detected in its ejecta.

Only about ten recurrent novae are known in our Galaxy, but this does not directly suggest a small population of recurrent novae. Recurrent nova eruptions develop so fast and their detections are not easy especially in their short bright phases. There are potentially a number of recurrent novae that are not yet identified as a recurrent nova (Pagnotta et al. 2009). All of the recurrent novae are now regarded as a thermonuclear runaway event owing to instability of hydrogen nuclear burning in a geometrically thin shell on a WD. Webbink et al. (1987) categorized recurrent novae into three subclasses, in which T CrB and RS Oph were modeled as a pair of an MS and an RG, but now it is clear that they are a binary consisting of a WD and an RG (Selvelli et al. 1992; Webbink 2008). Also a disk instability model of RS Oph outbursts (King & Pringle 2009; Alexander et al. 2011) is incompatible with many observational indications toward a thermonuclear runaway event (e.g., Nelson et al. 2011).

Table 1. Recurrent novae.

object [a]	outburst year	$P_{\rm rec}$ [b] (yr)	$P_{\rm orb}$ (day)	t_3 [c] (day)
CI Aql	1917,1941,2000	24	0.618	32
V394 CrA	1949,1987	38	1.52	5.2
V2487 Oph	1900,1998	98	~ 1	8
U Sco	1863,1906,1936,1945 1979,1987,1999,2010	8	1.23	2.6
T CrB	1866,1946	80	228	6
RS Oph	1898,1933,1958,1967 1985,2006	9	453.6	14
V745 Sco	1937,1989	52	510	9
V3890 Sgr	1962,1990	28	520	14
IM Nor	1920,2002	82	0.103	80
T Pyx	1890,1902,1920,1944 1966, 2011	12	0.076	62

Notes: (a) references for the objects are as follows. CI Aql: outburst year (Collazzi et al. 2009), $P_{\rm orb}$ (Mennickent & Honeycutt 1995). V394 CrB: $P_{\rm orb}$ (Schaefer 2009). V2487 Oph: outburst year (Pagnotta et al. 2009, who suggest the recurrence period to be possible 18 yr instead of 98 yr from discovery frequency), $P_{\rm orb}$ (Schaefer 2010). U Sco: Schaefer (2010) suggested 1917 and 1969 eruptions, $P_{\rm orb}$ (Schaefer 2010). T CrB: $P_{\rm orb}$ (Lines, Lines & McFaul 1988). RS Oph: Schaefer (2010) suggested 1907 and 1945 outburst, $P_{\rm orb}$ (Brandi et al. 2009). V745 Sco: $P_{\rm orb}$ (Schaefer 2009). V3890 Sgr: $P_{\rm orb}$ (Schaefer 2009). IM Nor: $P_{\rm orb}$ (Woudt & Warner 2003). T Pyx: $P_{\rm orb}$ (Schaefer et al. 1992).
(b) shortest recurrence period.
(c) all t_3 are taken from Schaefer (2010).

The recurrent novae are divided into three groups depending on the type of companion star:

1. Slightly evolved MS stars: CI Aql, V394 CrA, V2487 Oph, and U Sco.
2. Red-giant stars: T CrB, RS Oph, V745 Sco, and V3890 Sgr.
3. Red dwarf stars: IM Nor and T Pyx.

Here "slightly evolved MS" means that the companion star is a main-sequence star that has evolved off the zero-age main-sequence (ZAMS) and its radius has expanded a little. These three groups are sometimes called the U Sco, T CrB (or RS Oph), and T Pyx subclasses (e.g. Warner 1995), respectively. Table 1 lists the recorded outburst year, shortest recurrence period, orbital period, and t_3 time for all the Galactic recurrent novae ever reported, where t_m (m = 2 or 3) is the day during which a nova decays by m-th magnitude from optical maximum. Table 2 shows the WD mass estimated from the light curve analysis explained later in Section 3, t_2 time, distance d, extinction $E(B-V)$, apparent V magnitude at maximum $m_{V,\rm max}$, and absolute V magnitude $M_{V,\rm max}$ at maximum, and difference between the absolute V maximum observed and

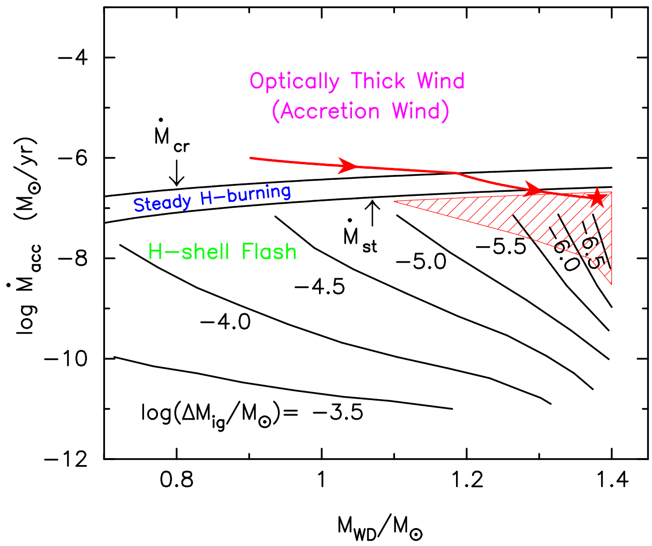

Figure 2. An evolutionary path of typical SN Ia progenitors (red solid line with arrows) on the map of WD responses to the mass accretion rate $\dot{M}_{\rm acc}$. The progenitor evolves from the optically thick wind phase, through SSS phase (steady H-burning phase) and recurrent nova phase (H-shell flash phase), and finally explodes as an SN Ia at star mark. In the region above the line of $\dot{M}_{\rm cr}$ ($\dot{M}_{\rm acc} > \dot{M}_{\rm cr}$), strong optically thick winds blow, which stabilize binary evolution in the SD scenario. On the other hand, a common envelope is formed in the original DD scenario, which results in a binary consisting of a double degenerate (WD) system. In the region of $\dot{M}_{\rm st} \leq \dot{M}_{\rm acc} \leq \dot{M}_{\rm cr}$, we have steady hydrogen shell burning with no optically thick winds. There is no steady-state burning below the line of $\dot{M}_{\rm st}$ ($\dot{M}_{\rm acc} < \dot{M}_{\rm st}$). Instead, hydrogen shell-burning intermittently occurs and results in a nova outburst. The envelope mass $\Delta M_{\rm ig}$, at which an intermittent hydrogen shell flash ignites, is also shown. Shadow area schematically shows the region in which the recurrence period is shorter than 100 yr, that is, the region of recurrent novae. The original data are taken from Nomoto (1982), Hachisu & Kato (2001a), and Hachisu et al. (2010).

the *V* maximum calculated from the MMRD relation. We added three related objects in order to compare them with the Galactic recurrent novae. Recurrent novae in the LMC and M31 are not listed in these Tables.

Note that in order to classify a nova into the subgroup of recurrent novae, just a rapid decline in the light curve, which suggests a massive WD, is not enough. For example, the classical nova V838 Her showed a light curve as steep as that of U Sco, also the light curve of V2491 Cyg decayed similarly to that of RS Oph. Their WD masses are estimated to be very massive, 1.35 $M_\odot$ for V838 Her (Kato et al. 2009), and 1.3 $M_\odot$ for V2491 Cyg (Hachisu & Kato 2009). However, these nova ejecta showed heavy element enrichment, Z = 0.12 for V838 Her (Vanlandingham, Starrfield & Shore 1997; Schwarz et al. 2007) and Z = 0.14 for V2491 Cyg (Munari et al. 2011), suggesting a long recurrence period between nova outbursts during which diffusion processes

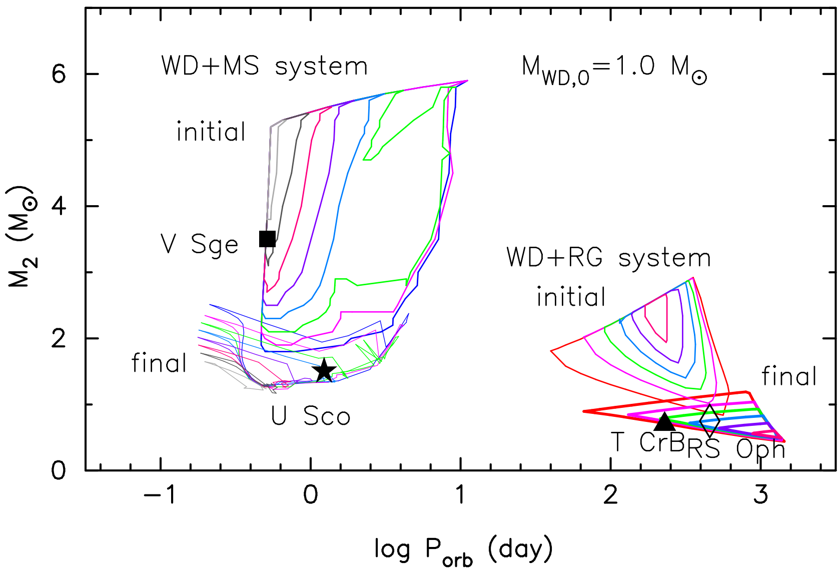

Figure 3. Initial and final binary parameter ranges proposed by a recent SD scenario (Hachisu et al. 2012b). Here, M_2 is the companion mass and $P_{\rm orb}$ the orbital period. An initial binary system inside the region encircled by a solid line (labeled "initial") is increasing its WD mass up to the mass of $M_{\rm WD}$ = 1.38, 1.5, 1.6, ..., 2.1, and 2.2 $M_\odot$ (from outside to inside) and then reaches the regions labeled "final" when the WD stops growing in mass. Currently known positions of recurrent novae and supersoft X-ray sources are indicated by star mark (⋆) for U Sco (e.g., Hachisu et al. 2000a), filled square for V Sge (Hachisu & Kato 2003b), filled triangle for T CrB (e.g., Belczyński & Mikolajewska 1998), and open diamond for RS Oph (e.g., Brandi et al. 2009). In the very last stage, the companion mass is reduced to 1–2 $M_\odot$ for the WD+MS systems, and $\lesssim 1\ M_\odot$ for the WD+RG systems.

work to dredge up WD core material into hydrogen-rich envelope. V2491 Cyg also showed a much shorter SSS phase (10 days) than that of RS Oph (60 days). A relatively long duration of a SSS phase stems from a mass-increasing WD (Kato 2012, see Section 3.3) while a relatively short one indicates a mass-decreasing WD as in normal classical novae. Therefore, both V838 Her and V2491 Cyg are highly likely classical novae rather than recurrent novae.

3. Theory of nova outbursts

3.1 Stability of shell flashes

A mass-accreting WD has a geometrically thin envelope before a nova eruption. The envelope is usually cold because of radiative cooling. As the envelope mass increases with time, the bottom of the envelope is gradually heated up due to compressional heating (gravitational energy release). When the envelope mass reaches a critical value, the radiative cooling almost balances with the

Table 2. WD mass in recurrent novae and related objects.

object [a]	WD mass ($M_\odot$)	t_2 [b] (day)	distance (kpc)	$E(B-V)$ [c]	$m_{V,\max}$	$M_{V,\max}$	$\Delta M_{V,\mathrm{MMRD}}$ (1), (2)
CI Aql	~ 1.2	25.4	4.7	0.85	8.8	−7.2	−0.3, −0.4
V394 CrA	$\gtrsim 1.37$	2.4		0.25	7.2		
V2487 Oph	$\gtrsim 1.37$	6.2		0.76[d]	9.5		
U Sco*	$\gtrsim 1.37$	1.2	6.7	0.35[d]	7.7	−7.5	−3.0*, −1.5
T CrB*	$\gtrsim 1.35$	4.0	0.96	0.065	2.5	−7.6	−2.4*, −1.3
RS Oph	~ 1.35	6.8	1.6	0.75[d]	4.8	−8.5	−0.9, −0.3
V745 Sco	$\gtrsim 1.35$	6.2		0.82[d]	9.4		
V3890 Sgr	$\gtrsim 1.35$	6.4		0.56[d]	8.1		
IM Nor		50.0	3.4	0.80	8.5	−6.7	−0.3, −0.4
T Pyx		34.6	3.2	0.25	6.3	−7.0	−0.2, −0.3
V407 Cyg*	$\gtrsim 1.37$	5.9	2.7	0.50	7.1	−6.6	−3.0*, −2.3
V838 Her	~ 1.35	1.4	4.0	0.43[d]	5.4	−8.9	−1.6, −0.1
V2491 Cyg	~ 1.3	4.8	13.0	0.23	7.5	−8.8	−0.9, −0.1

Notes: (a) references for the objects are as follows. CI Aql: WD mass (Hachisu & Kato 2001a), distance (Hachisu & Kato 2012b). V394 CrB: WD mass (Hachisu & Kato 2000). U Sco: WD mass (Hachisu et al. 2000a) but a super-Chandrasekhar mass WD is suggested by Hachisu et al. (2012a), distance (Hachisu et al. 2000a,b). T CrB: WD mass (Hachisu & Kato 2001b), distance and $E(B-V)$ (Belczyński & Mikolajewska 1998). RS Oph: WD mass (Hachisu et al. 2006; Hachisu & Kato 2006), distance (Hjellming et al. 1986). V745 Sco: WD mass (Hachisu & Kato 2001b). V3890 Sgr: WD mass (Hachisu & Kato 2001b). T Pyx: distance (Hachisu & Kato 2012b). V407 Cyg: WD mass (Hachisu & Kato 2012a), t_2 and distance (Munari et al. 2012), $E(B-V)$ (Shore et al. 2011). V838 Her: WD mass (Kato, Hachisu & Cassatella 2009), t_2 (Harrison & Stringfellow 1994), distance is calculated from the results of Kato et al. (2009) and the present value of $E(B-V)$. V2491 Cyg: WD mass (Hachisu & Kato 2009), t_2 (Munari et al. 2011), distance is calculated from the same method in Hachisu & Kato (2012b), $E(B-V)$ (Munari et al. 2011).
(b) all t_2 for recurrent novae are taken from Schaefer (2010) unless otherwise specified.
(c) all $E(B-V)$ for recurrent novae are taken from Schaefer (2010) unless otherwise specified.
(d) $E(B-V)$ is obtained from the Galactic dust absorption map of NASA/IPAC (http:// irsa.ipac.caltech.edu/ applications/DUST/).

total release of gravitational and nuclear burning energies. In such a situation, even a very small increase in the temperature causes a large increase in the nuclear burning energy release. This increase in the energy release cannot be dissipated away by radiation, and so results in a runaway of hydrogen nuclear burning. This is the beginning of a nova outburst.

The ignition mass of hydrogen-rich envelope is obtained from the condition that the radiative cooling is balanced with the total release of gravitational and nuclear burning energies. This ignition mass depends on the WD mass, mass accretion rate, WD temperature, and opacity (i.e., chemical composition) of the envelope. In recurrent novae, the ignition mass does not depend on the thermal history of the WD because the recurrence periods are shorter than ~ 100 yr. The ignition mass is smaller for a more massive WD because of its large compressional heating. Fig. 2

schematically depicts ignition masses by solid lines in the region of $\dot{M}_{\rm acc} < \dot{M}_{\rm st}$, where hydrogen shell burning is unstable.

During nova outbursts, all of the accreted matter will be blown off. Moreover, a part of the WD core is eroded due to diffusion of hydrogen into the core (see the next subsection). Then, the WD mass decreases after every nova outburst. In the case of recurrent novae, however, hydrogen shell flash is relatively weak and a certain amount of processed helium is added to the WD after every outburst. Therefore the WD mass increases (see Section 5.5). This recurrent nova region is indicated by shadow in Fig. 2. Their accretion rate is as large as $\dot{M}_{\rm acc} \sim 10^{-8}$–$10^{-7} M_\odot\ {\rm yr}^{-1}$ and the WD is quite massive ($M_{\rm WD} \gtrsim 1.1 M_\odot$).

When the mass accretion rate is larger than $\dot{M}_{\rm acc} \geq \dot{M}_{\rm st}$, hydrogen nuclear burning is stable and ash of hydrogen burning accumulates on the WD. When the mass accretion rate exceeds $\dot{M}_{\rm cr}$, the envelope expands to blow optically thick winds. The system undergoes an accretion wind evolution as illustrated in Fig. 1 while the binary was supposed to undergo a common envelope evolution in the original DD scenario.

Stability analysis of hydrogen shell-burning had been established a long time ago based on linear analyses by (Sienkiewicz 1975, 1980). His results were confirmed recently with the OPAL opacity (Nomoto et al. 2007). These stability criteria were also confirmed directly in many numerical calculations of shell flashes (Prialnik & Kovetz 1995; Jose & Hernanz 1998). Starrfield et al. (2004), however, presented an opposite result that all accreting WDs are thermally stable (this means that no novae/recurrent novae occur), thus, that the accreting WDs always grow in mass to reach the Chandrasekhar mass (Starrfield et al. 2004). Their calculations were criticized by Nomoto et al. (2007) for the reason that their results are artifacts originating from the lack of sufficient numerical grids. Recently, the same group (Starrfield et al. 2012) presented a completely different result to their previous one that all accreting WDs are unstable for shell flashes and virtually no SSS phase exists in classical novae. Again their results are not supported by the stability analysis cited above as well as many observed SSS phases of classical novae/recurrent novae (see, e.g., Henze et al. 2010, 2011, for an M31 nova survey).

For the last, we must note an inappropriate statement on the "proper pressure", which is widely used in estimating the ignition mass of novae (e.g. Osborne et al. 2011); there is a supposed simple relation between the pressure at the bottom of an envelope and the ignition mass, $P^* = (GM_{\rm WD}M_{\rm env})/(4\pi R_{\rm WD}{}^4) \sim 2 \times 10^{19}$ dyn cm^{-2}, where P^* is called the "proper pressure", $M_{\rm WD}$ is the WD mass, $M_{\rm env}$ the hydrogen-rich envelope mass, $R_{\rm WD}$ the WD radius. Thus the ignition mass is independent of the mass-accretion rate. This relation may originate from a formalism proposed by Shara (1981) and the numerically obtained critical pressures which were based on a simple envelope model of polytropic/adiabatic approximations by MacDonald (1983) and Fujimoto (1982). This simple expression, however, has discrepancy of envelope mass as large as an order of magnitude or more. Numerical results obtained with non-adiabatic, dynamical calculations with the OPAL opacity clearly show that the ignition condition is largely different from the "proper pressure" and depends on the mass accretion rate (e.g. Prialnik & Kovetz 1995).

3.2 Chemical composition of ejecta

Classical novae show heavy element enrichment in their ejecta by an amount of a few to several tens of per cent by mass (e.g., Gehrz et al. 1998). The enrichment is interpreted as dredge-up of WD core material into ejecta: Hydrogen diffuses into WD cores during the accreting phase and ignites below the original WD core surfaces, thus a part of core material is mixed by convection into the hydrogen-rich envelope and blown off in ejecta (Prialnik 1986). The diffusion occurs when $\dot{M}_{\rm acc} \lesssim 10^{-9}\ M_\odot\ {\rm yr}^{-1}$, i.e., in a long timescale of $M_{\rm env}/\dot{M}_{\rm acc} \sim 10^{-4}\ M_\odot/\dot{M}_{\rm acc} \gtrsim 10^5$ yr for classical novae. Therefore, the diffusion process is not effective in recurrent novae, in which the recurrence periods are as short as 10–100 yr. Thus, heavy element enhancement is not expected.

Recurrent novae, however, possibly show hydrogen depletion. In the very beginning phase of a nova outburst, convection widely develops and carries processed helium up into the envelope. This convective mixing reduces the hydrogen content by 10%–20% by mass for massive WDs like in recurrent novae. Therefore, we expect the hydrogen content of $X \approx 0.50$ and the solar metallicity of $Z \approx 0.02$ in envelopes of recurrent novae.

Because dredge-up of WD core material is not theoretically expected in recurrent novae, it is hard to know whether WDs in recurrent novae are made of carbon and oxygen (CO) or of oxygen, neon, and magnesium (ONeMg). This is important from the SN Ia progenitor point of view, because only CO WDs can explode as an SN Ia while ONeMg WDs will collapse to a neutron star (Nomoto & Kondo 1991). In the SD scenario, recurrent novae contain either a CO WD (increased from a initial WD mass of $\lesssim 1.07\ M_\odot$, see e.g., Umeda et al. 1999, for an upper limit of CO WD masses) or an ONeMg WD. In the DD scenario, all of the massive WDs ($\gtrsim 1.07\ M_\odot$) would be an ONeMg WD, because WDs hardly grow in mass during and after a common envelope phase.

Recently, Mason (2011) claimed that U Sco harbours an ONeMg WD because of a high Ne/O line ratio in spectra of the 2010 outburst, comparable to those in several neon novae, but much larger than those in CO novae. Unfortunately there are no such data in other recurrent novae other than classical novae. As we show later in Section 4, recurrent novae have a very different evolutionary history from those of classical novae. Mass-increasing WDs like in recurrent novae develop a thin helium layer underneath the hydrogen burning zone. After the helium shell grows in mass to reach a critical value, a helium shell flash occurs (e.g., Kato & Hachisu 1989). Helium burning produces a substantial amount of Ne and Mg (Shara & Prialnik 1994). Even if the WD is made of carbon and oxygen, the hydrogen-rich envelope could be contaminated with neon and magnesium. Therefore, some recurrent novae would show neon enhancement if it occurs shortly after the latest helium shell flash, because helium accumulation after every recurrent nova outburst could hide or dilute the products of helium shell flashes. Large Ne/O line ratios of ejecta do not always indicate an ONeMg WD. Instead, it may indicate that a CO WD develops a helium layer during every recurrent nova outburst. We suggest that the high Ne/O line ratio in U Sco (Mason 2011) is also an evidence of mass-increasing WD, although we need more observational information on the chemical compositions of U Sco and the other recurrent novae.

3.3 Light curve analysis of recurrent novae: how to determine white dwarf mass

After hydrogen burning sets in, the envelope rapidly changes its structure from a geometrically thin shell to a bloated spherical configuration. As the envelope expands from the WD surface to a red-giant size, the photospheric temperature rapidly decreases down to $\log T$ (K)$\sim$ 4.0 or lower. This spherically extended configuration is stable against hydrogen shell burning. Then the nuclear burning settles in a steady-state. The envelope mass decreases owing to nuclear burning and wind mass-loss. The hydrogen burning continues until the envelope mass decreases to reach a critical value for the extinguish condition. In this decay phase, the photospheric radius gradually shrinks whereas matter goes away. So the photospheric temperature increases with time (Kato & Hachisu 1994; Kato 1999). After the wind stops, the envelope mass still continues to decrease owing to nuclear burning. This stage corresponds to a SSS phase because the temperature is high enough to emit supersoft X-rays. At the termination of nuclear burning, the envelope structure comes back to a geometrically thin shell.

In the decay phase of nova outbursts, free-free emission of optically thin ejecta dominates continuum flux (e.g., Gallagher & Ney 1976). Hachisu & Kato (2006) modeled free-free emission light curves of novae based on the optically thick wind model calculated by Kato & Hachisu (1994). The decline rate of the model light curves depends sensitively on the WD mass and weakly on the chemical composition of envelope (Hachisu & Kato 2006). Especially, when the WD mass is close to the Chandrasekhar mass limit $M_{\rm Ch} \approx 1.4\ M_\odot$, the light curve depends sharply on the WD mass. This is because the WD radius is very sensitive to the increase in mass near $M_{\rm Ch}$. Therefore, we can in principle determine the WD mass by fitting the model light curve with the observed one (see, e.g., Hachisu & Kato 2010).

Here, we should note that dynamical calculations of nova outbursts have numerical difficulties, especially in the treatment of surface boundary condition. Nariai et al. (1980) already pointed out that expansion velocities are very different among different groups (see their Table 4). We note that Israel code (Idan, Shaviv & Shaviv 2012) tends to derive violent outbursts with large expansion velocities and large mass-loss rates, due to inadequate boundary conditions instead of solving the envelope up to the photosphere. No dynamical code has been succeeded so far in calculating extended stages of nova outbursts and their light curves. On the other hand, the optically thick wind theory was developed in order to calculate such extended stage of nova outburst and has been succeeded in reproducing a number of nova light curves (Hachisu et al. 2006; Hachisu & Kato 2006, 2007; Hachisu, Kato & Cassatella 2008; Kato et al. 2009) as well as expansion velocities (see Fig. 18 in Hachisu & Kato 2007).

One of the characteristic properties of recurrent nova light curves is a mid-plateau phase, that lasts 10 – 60 days after the brightness has decayed by several magnitudes. The plateau phase often overlaps with a SSS phase, i.e., it begins/ends when the supersoft X-ray flux rises/decays (e.g., Hachisu, Kato & Luna 2007; Osborne et al. 2011; Ness et al. 2012). Such plateau phases can be explained by the contribution of an irradiated disk as demonstrated by Hachisu et al. (2000a) for U Sco and by Hachisu et al. (2006, 2007) for RS Oph. The presence of an accretion disk is also suggested in T CrB, in which the secondary maximum in its light curve can be interpreted as the contribution from an irradiated large tilting-disk (Hachisu & Kato 1999). On the other hand, in classical novae, such mid-plateau phases are rarely reported. The contribution of disks is also suggested in classical novae, but it appears only in a very late phase of nova outbursts (see, e.g., Hachisu, Kato & Kato 2004, for V1494 Aql). It is because the orbital period is usually much shorter in classical novae than in recurrent novae, and thus classical novae have much smaller disks that do not contribute much to optical light curves.

We think that accretion disks are not entirely blown off during the outburst in recurrent novae. One of the indications is the presence of these mid-plateau phases. All the recurrent novae shows more or less a plateau phase. The other indications are the detection of flickering 8 days after the U Sco 2010 eruption (Worters et al. 2010) and formation of accretion disk at least 8 days after the 2010 outburst of U Sco (Mason et al. 2012). During the mid-plateau phase, orbital light curves of U Sco have asymmetric multiple-peak shapes outside the eclipse (Schaefer et al. 2012), which can be reproduced by spiral arm structure on the accretion disk (see, e.g., Hachisu et al. 2004, for V1494 Aql). Therefore, it is very likely that the disk was not gone but survived during the 2010 outburst. On the other hand, some numerical calculations indicated that the accretion disk is entirely disrupted by the fast moving ejecta (Drake & Orlando 2010). This seems to be inconsistent with the presence of the disk only 8 days after the outburst. We suppose that numerical calculation cannot resolve the accretion disk that has high density region near the equator.

Outburst light curves of recurrent novae are a summation of each contribution from a WD, irradiated accretion disk, and irradiated companion. Such composite light curves are modeled for RS Oph by Hachisu et al. (2006), U Sco by Hachisu et al. (2000a), T CrB by Hachisu & Kato (1999), V394 CrA by Hachisu & Kato (2000), and CI Aql by Hachisu & Kato (2001a). The resultant WD masses are listed in Table 2.

3.4 Maximum magnitude versus rate of decline relation

There is a statistical relation between the maximum V magnitude, $M_{V,\max}$, and the rate of decline, t_2 or t_3, in optical light curves of classical novae (e.g., Schmidt 1957; Della Valle & Livio 1995). This is called the MMRD relation. Distribution of individual novae in the t_3–$M_{V,\max}$ plane shows a main trend from the left-top to the right-bottom but there is a large scatter above/below the main trend (e.g., Downes & Duerbeck 2000; Kasliwal et al. 2011). Hachisu & Kato (2010) theoretically explained the main trend and scatter of the MMRD relation. The main parameter that determines the main trend is the WD mass, and the second parameter for the scatter is the ignition (initial envelope) mass, in other words, the mass accretion rate to the WD. If the mass-accretion rate to the WD is relatively larger, the ignition mass is smaller (see Fig. 2), so that the peak brightness is fainter. This second parameter can reasonably explain the scatter of individual novae (see, e.g., Fig. 15 of Hachisu & Kato 2010).

It is, however, frequently discussed that the MMRD relation cannot be applied to recurrent novae. Table 2 show the difference between the absolute V magnitude and what the MMRD predicts, that is, $\Delta M_{V,\mathrm{MMRD}} = M_{V,\mathrm{MMRD}} - M_{V,\max}$, for six recurrent novae and three very fast classical novae. Here we estimate the absolute V magnitude $M_{V,\max}$ using the distance and extinction in Table 2. For the MMRD relation, we use (1) Downes & Duerbeck (2000), that is, $M_{V,\mathrm{MMRD}} = -10.79 \pm 0.92 + (1.53 \pm 1.15) \log t_2$ for faster novae ($\log t_2 \leq 1.2$), but $M_{V,\mathrm{MMRD}} = -8.71 \pm 0.82 + (1.03 \pm 0.51) \log t_2$ for slower novae ($\log t_2 \geq 1.2$), and also, for comparison, (2) Della Valle & Livio (1995), that is, $M_{V,\mathrm{MMRD}} = -7.92 - 0.81 \arctan((1.32 - \log t_2)/0.23)$. Four recurrent novae, CI Aql, RS Oph, IM Nor, and T Pyx show reasonable agreement (within 1 σ error) with what two MMRD relations (1) and (2) predict. Two classical novae V838 Her and V2491 Cyg also show good agreement with what MMRD relation (2) predicts.

On the other hand, U Sco and T CrB have a very similar absolute V magnitude at maximum, $M_{V,\max} = -7.5$ and -7.6, respectively, and both of them show a large deviation from the MMRD prediction. Even if we use MMRD relation (2), the absolute magnitude of U Sco is still 1.5 mag fainter than the prediction. The symbiotic classical nova V407 Cyg also shows a very large deviation from the MMRD relation. We think that these large deviations from the MMRD relation are one of the indications of super-Chandrasekhar mass WDs (Section 6.1) because a large deviation means a small envelope mass at the optical peak (i.e., small ignition mass), which is a strong indication of very massive WDs as explained in section 3.1.

4. Evolutionary status of recurrent novae

In this section, we discuss the evolutionary status of recurrent nova systems and how they will evolve toward SN Ia explosions. In the original DD scenario, there are no known paths to recurrent novae especially for the RS Oph type systems. In the SD scenario, there are two channels to SNe Ia, i.e., the WD+MS (or simply MS) channel and WD+RG (or symbiotic) channel. In the MS channel, a pair of MS stars evolve to a binary consisting of a helium star plus an MS star after the first common envelope evolution (e.g., Hachisu et al. 1999b). The primary helium star further evolves to a helium RG with a CO core and fills its Roche lobe followed by a stable mass-transfer from the primary helium RG to the secondary MS star. The secondary MS star increases its mass and is contaminated by the primary's nuclear burning products. The primary becomes a CO WD after all the helium envelope is transferred to the secondary MS star. Then the secondary evolves to fill its Roche lobe and mass transfer begins from the secondary MS (or subgiant) star to the primary CO WD. When the mass-transfer rate exceeds $\dot{M}_{\mathrm{cr}}$, an accretion wind evolution is realized. The mass-transfer rate gradually decreases to below $\dot{M}_{\mathrm{cr}}$ and the optically thick winds stop. Then all the accreted matter is burned on the primary CO WD. The binary enters a persistent supersoft X-ray source (SSS) phase. We should note that we must distinguish this persistent SSS phase from transient SSS phases in classical novae and recurrent novae. The mass-transfer rate further decreases to below $\dot{M}_{\mathrm{st}}$ and the binary enters a recurrent nova phase.

In Fig. 3, binaries within the area labelled "initial" evolve downward and reaches the "final" area when its mass increases to $M_{\mathrm{WD}} > 1.38\ M_\odot$. The supersoft X-ray source V Sge and RX J0513.9-6951 are regarded as a binary corresponding to the accretion wind phase (Hachisu & Kato 2003a,b), i.e., these binaries are now evolving toward SNe Ia. The present status of U

Sco and other recurrent novae in Table 1 corresponds to the final stage of the above three phases (wind, SSS, and recurrent nova). If a WD explodes during the wind phase, the resultant SN Ia shows some indications of the interaction between ejecta and circumstellar matter (CSM) and the presence of hydrogen, because the WD winds and matter stripped from the companion should form a rather massive CSM. If it explode during the SSS or recurrent nova phase, there are weak indications of hydrogen because the secondary MS mass are $\sim$ 1–2 $M_\odot$ and their size is compact. In multidimensional dynamical calculations of SN Ia explosion, however, a very massive companion is often assumed (e.g. Kasen 2010, 2 - 6 $M_\odot$ MS) and they conclude that the SD scenario is inconsistent with no UV excesses as well as no detections of hydrogen lines. However, we think that these secondary masses are rather large and not realistic.

In recent SN Ia progenitor models of Justham (2011), Di Stefano, Voss & Claey (2011), and Hachisu et al. (2012b), they suppose that a rapidly rotating WD does not explode as an SN Ia even if it exceeds $M_{\rm WD}$ = 1.38 $M_\odot$, because the central density is too low to ignite carbon. They further assume that it takes a long time before the SN Ia explosion. Once it exceeds $M_{\rm WD}$ = 1.38 $M_\odot$, then the explosion is postponed until it spins down and the central density increases to reach a critical density for carbon ignition. During such a long waiting time, the companion evolves off the main-sequence and become a WD or transfers its mass to the primary WD and becomes a cataclysmic variable with a short orbital period. When the primary WD explodes as an SN Ia, neither hydrogen nor a bright ex-companion is left, but only a rather dark WD or a red dwarf ex-companion is left. Hachisu et al. (2012b) showed that such a dark ex-companion is in a majority of SN Ia remnants coming from the MS channel.

In the symbiotic channel we start from a very wide binary in which the primary evolves to an asymptotic giant branch (AGB) star. The binaries undergo a common envelope-like evolution during the superwind phase of the primary AGB star (e.g., Hachisu et al. 1999a). The separation of the binary shrinks to the orbital period of 30 – 800 days and it becomes a pair of a CO WD and an MS star. Then the secondary MS evolves to a RG with a helium core and fills its Roche lobe. Then the system enters an accretion wind evolution. After that, the binary becomes a persistent SSS, and evolves finally to a recurrent nova. Depending on the binary parameters, the WD mass reaches $M_{\rm WD}$ = 1.38 $M_\odot$ during one of the three phases (wind, SSS, and recurrent nova). One of such evolutionary paths is plotted in Fig. 2 by a red solid line. The SMC symbiotic X-ray source SMC3 corresponds to the SSS phase and symbiotic recurrent novae like T CrB do the last phase. If the WD explodes as an SN Ia during the first two phases, hydrogen should be detected in the SN Ia explosion, because substantial amount of matter is stripped out from the RG (see, e.g., Kato, Hachisu & Mikolajewska 2012b, for SMC3). In the recurrent nova phase, however, the companion has already substantially exhausted its envelope through the long-lasted mass-transfer phase. Its envelope mass may be small ($\lesssim$ 0.5 $M_\odot$), because they have developed a helium core.

In the spin-up/spin-down scenario of SNe Ia, the SN explosion could be postponed until the secondary RG evolved off the red-giant branch and became a helium (or CO) WD. These dark companion WDs could not be detected just before and after the SN Ia explosion. Hachisu et al. (2012b) showed that in their rapidly spinning WD progenitor models, these dark companions are the majority of SN Ia progenitors. Therefore, we cannot expect any indication of hydrogen or bright companions in such SN Ia explosions.

Observations of SNe Ia have provided the following constraints on the nature of companion stars. Some evidences support the SD model, such as the presence of circumstellar matter (Patat et al. 2007; Sternberg et al. 2011; Foley et al. 2012) and detections of hydrogen in the circumstellar matter-ejecta interaction type SNe (type Ia/IIn) like SN 2002ic (Hamuy et al. 2003), SN 1604 (Kepler's SNR) (Chiotellis, Schure & Vink 2012), and PTF11kx (Dilday et al. 2012). On the other hand, there has been reported no direct indication of the presence of companions, which is usually thought to be unfavorable for the SD scenario, e.g., (1) the lack of companion stars in the images of SN 2011fe (Li et al. 2011), some SN Ia remnants (SNRs) (Schaefer & Pagnotta 2012), SN 1572 (Tycho's SNR) (Kerzendorf et al. 2009) and SN 1006 (Kerzendorf et al. 2012), (2) the lack of UV excesses of early-time light curves (Kasen 2010), and (3) the lack of hydrogen features in the spectra (Leonard 2007). Both (2) and (3) are expected from the collision between ejecta and a companion. Hachisu et al. (2012b) showed that their SD scenario mainly produces unseen companions at SN Ia explosion because of a long spin-down time. They also showed that the WD mass distribution at SN Ia explosion predicted by their model agrees well with the distribution of SN Ia brightness observed if the brightness is correlated to the WD mass. These results strongly support that a major route to SNe Ia is the SD system and they explode through a recurrent nova stage.

5. Elementary processes in binary evolution

The SD scenario is based on different elementary processes from those assumed in the original DD scenario, which result in a very different binary evolution as well as population synthesis. Thus, it is important to clarify theoretical backgrounds of each elementary process. In this section, we critically examine each elementary process based on the results of nova studies, because many of these ingredients are closely related to nova phenomena.

5.1 Common envelope evolution

Common envelope evolution is a fundamental process of binary evolution for both the SD and DD scenarios. The first common envelope evolution in a binary occurs when the primary star evolves to a red-giant and fills its Roche lobe. Common envelope evolutions were formulated in a very simple form based on the total energy conservation (gravitational energy of the orbit plus envelope binding energy) before and after the common envelope evolution. The ratio of the binary orbit before (*initial*) and after (*final*), A_f/A_i, is given by a simple form using an efficiency parameter $\alpha(< 1)$ (e.g. Iben & Livio 1993). A smaller value of α leads to a smaller ratio of A_f/A_i, i.e., a larger shrinkage of the binary orbit. In the original α-formalism, α is only the parameter. Some authors had a different expression to calculate the gravitational energy of the RG envelope by using λ-parameter (Webbink 1984; de Kool 1990), which represents the effective mass-weighted radius of RG stars. Then the product of $\alpha\lambda$ behaves like the original α. Observationally, Zorotovic et al. (2010) derived $\alpha = 0.2$–0.3, assuming that α is universal together with $\lambda = 0.5$, while Rebassa-Mansergas et al. (2012) obtained $\alpha \sim 0.25$. De Marco et al. (2011) obtained the dependence of α on the mass ratio $q = M_2/M_1$ such as $\alpha \sim 1$ for $q = 0.1$, $\alpha \sim 0.2$ for $q = 0.3$, and $\alpha \lesssim 0.1$ for $q = 1$. These new α-parameters work together with the effective radius parameter of λ, for example, $\lambda = 0.4$ for $M_1 = 5\ M_\odot$ or $\lambda = 0.45$ for $M_1 = 7\ M_\odot$ of AGB stars (e.g., De Marco et al. 2011). These recent analyses suggest that $\alpha\lambda \sim 0.1$–0.2. In many population synthesis calculations that support the DD scenario, however, a larger value of $\alpha\lambda \sim 1$ was preferentially used independently of q, because such a larger value yields a larger birth rate of SNe Ia in their DD models (e.g., Ruiter et al. 2009). It is however interesting that the birth rate of SNe Ia coming from SD binaries increases and becomes comparable to the rate coming from DD binaries if we have a smaller value of $\alpha\lambda \lesssim 0.5$ (e.g., Ruiter et al. 2009). This suggests that if we adopt a realistic value of $\alpha\lambda$ such as $\alpha\lambda \sim 0.1$, the SD binaries dominate the progenitors of SNe Ia in population synthesis.

One of the recent trends in the population synthesis community is to assume an extremely large value of α (> 1) (Hurley, Tout & Pols 2002; Tout 2005; Meng & Yang 2012). If there is a large additional energy source (e.g., recombination energy), the binary separation will even increase after the common envelope evolution (Webbink 2008). However, such a mechanism seems to be very difficult to work effectively because it needs all the envelope matter instantaneously recombined in the accelerating zone and the released energy efficiently converted to the binding energy without radiative loss (see, e.g., a criticism by Soker & Harpaz 2003). This idea may be introduced in order to reproduce symbiotic recurrent nova systems in the DD scenario (Webbink 2008). However, recent observational estimates, $\alpha\lambda \sim 0.1$ for AGB stars, do not support such an extremely high value of $\alpha\lambda$ (> 1) (e.g., Zorotovic et al. 2010).

Nelemans et al. (2000) proposed a new formalism for common envelope evolution based on the assumption that angular momentum loss is proportional to the amount of lost mass, $\Delta J/J = \gamma \Delta M/M$. This formalism contains a proportionality parameter γ, so dubbed "γ-formalism". This formalism is criticized by Webbink (2008) as it does not actually limit A_f. Zorotovic et al. (2010) also criticized the γ-formalism because the α-formalism is much more reasonable from the statistics of a large number of binary parameters.

5.2 Accretion wind evolution versus common envelope evolution

After the first common envelope evolution, the binary becomes a pair of a WD and a secondary star. After some time elapses, the secondary evolves to fill its Roche lobe. Then the mass transfer begins from the secondary to the primary WD through the L1 point. Infalling matter forms an accretion disk and finally accretes on to the WD. The accreted matter quickly spreads over the entire WD surface and hydrogen nuclear burning ignites after some critical amount of mass accumulates. If the secondary is an evolved RG more massive than the WD, the mass accretion rate exceeds the critical value, $\dot{M}_{\rm cr}$ (see Fig. 2), and strong optically thick winds blow. Once the wind occurs, the wind carries away mass and angular momentum. Then the orbital separation and the size of the secondary's Roche lobe change in time. The mass-transfer rate is regulated to keep the secondary's radius equal to the Roche lobe radius. If the mass-transfer rate is smaller than $\dot{M}_{\rm acc} \lesssim 10^{-4}\ M_\odot\ {\rm yr}^{-1}$, a common envelope does not form (Hachisu et al. 1999a,b). This is the accretion wind evolution (Fig. 1). When the accretion rate is very large $\dot{M}_{\rm acc} \gtrsim 10^{-4}\ M_\odot\ {\rm yr}^{-1}$, however, the photospheric radius of the WD expands over the Roche lobe, and a common envelope evolution may occur.

If the accretion wind evolution is taken into account, the condition for the second common envelope evolution is relaxed to $q < 1.15$ from $q < 0.79$, where $q = M_{\rm RG}/M_{\rm WD}$. The former condition is obtained with the mass and angular momentum conservations including those of the winds, and the latter without the winds. Therefore, some binaries can avoid a formation of the second common envelope and keep the binary separation. The binary still consists of a mass-accreting WD and a lobe-filling secondary. The WD can grow in mass during the accretion wind evolution (Hachisu et al. 1996).

This is the first step that widens the binary parameter range of SN Ia progenitors. It is interesting to note that optically thick winds have been established in nova outbursts. The U Sco 2010 outburst suggested that an accretion disk formed (or still existed) in a very early phase, only 8 days after the optical maximum (see Section 3.3 and Mason et al. 2012). In this early phase, the optically thick wind had not yet stopped (it ends at around Day 13) but the companion and accretion disk emerged from the extended envelope at Day 8 (Hachisu & Kato 2012a). This means that accretion from the companion can be observed when the companion emerged from the WD photosphere, while the optically thick wind still continues. We think that this is an observational example of accretion wind evolution.

5.3 Mass stripping in accretion wind evolution

When the accretion wind occurs as illustrated in Fig. 1, the fast wind ($\gtrsim 1000$ km s^{-1}) hits the companion's surface that fills the Roche lobe. A very surface layer of the companion's hemisphere may be stripped by the winds, which reduces the mass outflow rate from the secondary. Hachisu et al. (1999a) first incorporated this effect into their binary evolution and established the symbiotic channel to SNe Ia. This is the second step that widens the parameter range of binary evolution toward SNe Ia.

The accretion wind evolution including the mass-stripping effect is also essential to understand the mechanism of quasi-periodic behavior of the two SSS binaries, V Sge and RX J0513.9−6951. Hachisu & Kato (2003a,b) explained both the optical and supersoft X-ray light curves of these two objects based on the accretion wind evolution that leads to a limit cycle of the light curve behavior. They obtained the WD masses of $\sim 1.2 - 1.3\ M_\odot$, and the mass-increasing rates of the WDs $\sim 10^{-6}\ M_\odot\ {\rm yr}^{-1}$ for the both objects from light curve fitting. Therefore, these two systems are also candidates of SN Ia progenitors. There are several similar objects in our Galaxy, the so-called V Sge-type stars (Steiner & Diaz 1998). Kafka, Anderson, Honeycutt (2008) and Linnell et al. (2008) found that QU Car is a very similar object to V Sge and belongs to the V Sge-type stars. This also suggests that many such objects could be misclassified to other categories of variable stars and the number of V Sge-type stars would significantly increase.

The successful results of limit-cycle light curves strongly suggest that (1) both the processes of "accretion wind" and "mass stripping" can be realized in binary evolution and (2) we expect a wider parameter region of binary evolution toward SNe Ia by avoiding the second common envelope evolution.

5.4 AGB super winds in wide binaries

Stars with a mass less massive than $M \lesssim 8\ M_\odot$ lose most of its envelope mass in a short timescale ($\lesssim 10^4$ yr) at the final stage (at its asymptotic giant branch, AGB, phase) of evolution. Hachisu et al. (1999a) incorporated this AGB superwind as an important process in binary evolution. Due to large mass-loss rates of superwinds (up to several $\times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, Groenewegen et al. 2002; Guandalini et al. 2006), even very wide binaries (a_i = 1500 – 30000 $R_\odot$) experience a decay of the orbital separation that is similar to a common envelope evolution. After that, it becomes a wide binary corresponding to the orbital periods of symbiotic stars. This is the symbiotic channel of the SD scenario first proposed by Hachisu et al. (1999a).

The original DD scenario did not include the evolution driven by superwinds in very wide binaries. Many population synthesis calculations still started from zero-age binaries excluding very wide binaries. Thus, after the first common envelope evolution, the separation shrinks from $a_i \sim$ 700–2200 $R_\odot$ to $a_f \sim$ 5–17 $R_\odot$ ($P_{\mathrm{orb}} \sim$ 0.5–1.5 days) if we use $\alpha\lambda \sim 0.1$ from the recent trend of small values of α (see Section 5.1). Then the resultant binary periods lie in the region of 0.5–1.5 days, which is not consistent with the present states of symbiotic recurrent novae but consistent with the MS channel of SD scenario. This is the reason why the SN Ia rate coming from SD binaries becomes large and exceeds the rate coming from DD binaries if we assume a small value of $\alpha\lambda$.

5.5 Mass increasing rate of white dwarfs

The original DD scenario was based on the mass increasing efficiency of WDs being very different from that of the SD scenario. In the original DD scenario, mass-accreting WDs can grow in mass only if they stay in the narrow strip region ($\dot{M}_{\mathrm{st}} \leq \dot{M}_{\mathrm{acc}} \leq \dot{M}_{\mathrm{cr}}$) in Fig. 2. These WDs, however, suffer helium shell flashes, which take away a large part of the helium envelope mass. Thus the total efficiency of mass-increase is very small. Such a small mass-increasing efficiency is based on the claim by Cassisi, Iben & Tornambe (1998) and Piersanti et al. (1999, 2000) who calculated shell flashes on low-mass WDs ($\lesssim 0.8 M_\odot$) using a spherical symmetric hydrostatic code with the Los Alamos opacity. They concluded that the frictional process due to the companion's motion should be very effective to take away most of the envelope mass, simply because the envelope photosphere expands beyond the binary orbit, although their calculation did not include any frictional effects in their codes.

It is worth noting that Cassisi et al. (1998) emphasized 'the Los Alamos opacities are very similar to the OPAL opacities' (see the last sentence of Section 4 in their paper). However, this is clearly an incorrect statement (see a comparison between nova envelopes calculated with the new and old opacities in Fig. 15 of Kato & Hachisu 1994). As we have already known, calculations with the old opacity could derive very different conclusions. Even in the same framework of 1980's physics, however, their claim was not supported by the results given by Kato & Hachisu (1989) and Kato (1991a,b). Now a days we have many calculational/observational indications that frictional processes are ineffective in nova outbursts [see, e.g., introduction in Kato & Hachisu (2011), Section 7.2 in Kato, Mikolajewska & Hachisu (2012), and also Section 6.2 of this review]. Cassisi et al. (1998) and Piersanti et al. (1999, 2000) extended their arguments on the low mass WDs ($\lesssim 0.8 M_\odot$) to all the WD masses up to the Chandrasekhar mass, as often cited like 'WDs are hardly grow to reach the Chandrasekhar mass limit due to frictional effects' (e.g. Straniero & Piersanti 2003; Yungelson 2005; Maoz & Badenes 2010) in the arguments against the SD scenario.

In the SD scenario, on the other hand, we have a much wider mass-growing region of WDs, not restricted into the narrow strip in Fig. 2 as in the original DD scenario. In addition to this narrow strip, WDs in the region above $\dot{M}_{\rm acc} = \dot{M}_{\rm cr}$ can grow in mass during the accretion wind evolution. It could also grow in the region slightly below the line $\dot{M}_{\rm acc} = \dot{M}_{\rm st}$, i.e., $10^{-8}\ M_\odot$ yr^{-1} $\lesssim \dot{M}_{\rm acc} < \dot{M}_{\rm st}$, where the shell flashes are weak. The mass increasing efficiency of WDs is obtained from the combination ($\eta_{\rm H}\eta_{\rm He}$) of the mass accumulation efficiencies of hydrogen shell burning/flashes $\eta_{\rm H}$ (Hachisu et al. 1999b; Prialnik & Kovetz 1995) and of helium shell burning/flashes $\eta_{\rm He}$ (Kato & Hachisu 2004).

Nelemans (2012) compared the total mass-increasing efficiency of a 1 $M_\odot$ WD between the DD and SD models. The mass increasing efficiency is up to $\eta_{\rm H}\eta_{\rm He} \sim 0.8$ in the SD models, but only $\eta_{\rm H}\eta_{\rm He} \sim 0.1$ at most (at $\log \dot{M}_{\rm acc}$ ($M_\odot$ yr^{-1}) ~ -6.6) in the model by Yungelson (2010) (see Fig. 4 in Nelemans 2012). The latter value is increased to $\eta_{\rm H}\eta_{\rm He} \sim 0.2$ (at $\log \dot{M}_{\rm acc} \sim -6.1$) for symbiotic stars (Iben & Tutukov 1996) because of their larger Roche lobe sizes. Now we can see where the difference comes from. The original DD model (Iben & Tutukov 1996) adopt the old opacity and instantaneous envelope mass ejection due to the Roche lobe overflow. Moreover, they assumed line-driven winds from the WD of very large mass-loss rate (with 100% efficiency of photon momentum flux, i.e., a few times $10^{-7} M_\odot$ yr^{-1}). We think that this rate is too large and unlikely. Such large mass-loss rates are not included in the SD scenario because no optically thick winds blow when $\dot{M}_{\rm acc} < \dot{M}_{\rm cr}$. As a results, the original DD scenario yields a very small efficiency of mass-growth of WDs even when they calculate SD binaries in their DD scenarios. Thus, the SD channel hardly contributes to the total SN Ia rate in the DD scenarios.

5.6 Other ingredients – accretion disk instability

King, Rolfe & Schenker (2003) presented an idea that thermal disk instabilities temporarily increase the mass accretion rate onto the WD, which would trigger steady hydrogen burning, thus, the lower line of the narrow strip "steady H-burning" in Fig. 2 would goes down as much as by −2.4 in logarithmic scale. However, this idea is based on a misunderstanding about the instability of hydrogen shell-burning (shell-flash). We should note that the same mistake was repeated in Alexander et al. (2011) after the criticism by Hachisu et al. (2010). As explained in Section 3.1, a shell flash occurs when the envelope mass increases to the ignition mass at which the thermal balance in the envelope breaks down. This does not occur only when the accretion rate temporarily exceeds $\dot{M}_{\rm cr}$. Unfortunately, this incorrect idea was already incorporated in some binary evolution models (Xu & Li 2009; Wan & Han 2010; Meng & Yang 2010), but these results have no astrophysical meaning.

6. Related objects

6.1 Super-Chandrasekhar mass white dwarfs – U Sco, T CrB and V407 Cyg

Recently super-Chandrasekhar mass WDs are suggested from observations of very luminous SNe Ia (e.g., Howell et al. 2006; Hicken et al. 2007; Yamanaka et al. 2009; Scalzo et al. 2010; Silverman et al. 2011; Taubenberger et al. 2011). In the SD scenario, WDs that exceed the Chandrasekhar mass limit are theoretically possible if they are rapidly rotating (e.g., Justham 2011; Di Stefano et al. 2011; Hachisu et al. 2012a,b, and references therein). If recurrent novae are progenitors of SNe Ia, some of them could be super-Chandrasekhar mass WDs. So far, only one object (U Sco) was suggested to harbor a super-Chandrasekhar mass WD (Hachisu et al. 2012a), but we here suggest two more objects, the symbiotic recurrent nova T CrB and symbiotic classical nova V407 Cyg.

The WD mass of U Sco was observationally estimated to be $M_{\rm WD} = 1.55 \pm 0.24\ M_\odot$ in the 1999 outburst (Thoroughgood et al. 2001). This value is very suggestive, although the ambiguity is too large to draw a definite conclusion of super-Chandrasekhar mass. There are additional indications of super-Chandrasekhar mass WD in U Sco. (1) The present binary parameters of U Sco shows that it just locates in the "final" stage of the path toward super-Chandrasekhar mass WDs in the SD scenario (Fig. 3), (2) The very fast decline of the optical nova light curve is consistent with a very massive WD as large as (or beyond) the Chandrasekhar mass limit of no rotation ($M_{\rm Ch} = 1.4\ M_\odot$). (3) The maximum brightness, $M_{V,\rm max} = -7.5$, is as much as 3.0 mag below the MMRD's prediction (Section 3.4). There is another candidate of super-Chandrasekhar mass WD, the symbiotic recurrent nova T CrB. The early decline of its light curve is so rapid and its maximum brightness shows a large deviation (2.4 mag) from the MMRD relation (see Section 3.4). We think this kind of large deviations ($\gtrsim$ 2.5 mag, denoted by asterisk in Table 2) from the MMRD relation is an indication of super-Chandrasekhar mass WD unless the estimated distance is largely different from the true one.

V407 Cygni is a long orbital period (D-type) symbiotic star consisting of a WD and a Mira (Munari et al. 2012). V407 Cyg outbursted as a classical nova in 2010 (Nishiyama et al. 2010). The optical light curve shows a very rapid decline in the very early phase which resembles that of U Sco. It entered a plateau phase only several days after the outburst and started the final decline 47 days after the outburst (Munari et al. 2012). Such an evolution of light curve is faster than that of RS Oph. Hachisu & Kato (2012a) modeled the optical light curve of V407 Cyg and suggested that the WD mass of V407 Cyg as massive as that of U Sco and its plateau phase can be reproduced by a large irradiated disk like in RS Oph (Hachisu et al. 2006). The peak absolute magnitude is calculated to be $M_{V,\rm max} = -6.6$ as in Table 2 and the MMRD error is as large as 3.0 mag almost similar to that of U Sco. Thus, we expect that V407 Cyg is also a candidate for super-Chandrasekhar mass WD.

Ejecta of the V407 Cyg 2010 nova outburst were enriched with heavy elements (Shore et al. 2011), suggesting that WD core material was dredged up and ejected. This means that the WD mass decreases after every nova outburst. Thus, V407 Cyg will possibly not explode as an SN Ia if the WD has a sub-Chandrasekhar mass. If the WD is composed of carbon and oxygen and has a super-Chandrasekhar mass, however, it could be a progenitor of SN Ia because even after many nova cycles the WD is still more massive than the Chandrasekhar mass and can explode soon after it spins down (Hachisu et al. 2012b). This kind of symbiotic progenitors can explain the interaction between SN Ia ejecta and circumstellar matter as seen in Kepler's supernova remnant (SNR) (Reynolds et al. 2007; Chiotellis et al. 2012) and in PTF 11kx (Dilday et al. 2012).

6.2 Helium nova V445 Pup

V445 Pup is a helium nova that underwent a helium shell flash (Kamath & Anupama 2002; Kato & Hachisu 2003; Ashok & Banerjee 2003; Woudt et al. 2009; Kato et al. 2008). The WD mass is estimated to be very massive $M_{\rm WD} \gtrsim 1.35\ M_\odot$, and the companion star is a slightly evolved helium star of mass $\gtrsim 0.8\ M_\odot$ (Kato et al. 2008). The orbital period is suggested to be $P_{\rm orb} = 0.65$ days (Goranskij et al. 2010). The WD is already as massive as (or close to) the Chandrasekhar mass and its mass is increasing after one cycle of helium nova. Therefore, this system is a candidate for SN Ia progenitors (Kato et al. 2008). Such a binary, however, does not fit to any known path in the binary evolution scenarios (for example, the final orbital periods are much shorter than 0.65 days in their helium star donor channel of Wang et al. 2009 and Wang & Han 2010b), indicating the unknown third path toward SNe Ia or some missing processes in binary evolution models of helium star donor channel.

In mass increasing WDs like in SSSs or in recurrent novae, we expect that a helium layer develops underneath the hydrogen burning zone. This helium layer periodically experiences helium shell flashes. V445 Pup indicates that some accreting WDs can become very massive and neither helium nor carbon detonation has ever occurred at the bottom of the helium layer. This does not support the idea that accreting WDs cannot grow in mass due to frictional process, which is frequently assumed in the DD scenarios in order to reject the SD scenarios.

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