Part V

Supersoft Sources as SN Ia Progenitors

Type Ia Supernovae and Supersoft X-ray Sources

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Abstract. The question of the possible progenitors of supernovae Type Ia (SNe Ia) is examined in the light of the existence of supersoft X-ray sources. It is argued that SNe Ia are thermonuclear explosions of accreting C-O white dwarfs. The existing observational evidence favors somewhat models in which the exploding star ignites carbon upon reaching the Chandrasekhar mass. A careful examination of all the potential progenitor classes reveals that when realization frequencies are combined with a variety of observational charcteristics, no *single* class emerges as containing the obvious progenitors. It is argued that coalescing white dwarfs or supersoft X-ray sources are the most likely progenitor systems. A few critical observations which could help identify the progenitors unambiguously are discussed.

1 Characteristics and the Basic Model

The *defining* characteristics in the spectra of supernovae Type Ia (SNe Ia) are the lack of lines of hydrogen and the presence of a strong red Si II absorption feature (λ6355 shifted to $\sim$ 6100Å). The following are some of the observational characteristics of the class:

(1) Nearly 90% of all SNe Ia form a homogeneous class in terms of their spectra, light curves and peak absolute magnitudes. The latter are given by $M_B \simeq M_V \simeq -19.75 + 5\log(H_o/50\ \mathrm{km\,s^{-1}\,Mpc^{-1}})$, with a dispersion of $\sigma(M_B) \sim \sigma(M_V) \sim 0.2$ (*e.g.* Tammann & Sandage 1995).

(2) Near maximum light, the spectra are characterized by high velocity (8000–30000 km s^{-1}) intermediate mass elements (O-Ca). In the late, nebular phase, the spectra are dominated by forbidden lines of iron (*e.g.* Kirshner *et al.* 1993; Wheeler *et al.* 1995; Ruiz-Lapuente *et al.* 1995a).

(3) In terms of explosion strength, SNe Ia can be roughly ordered as: SN 1991bg and SN 1992k represent the weakest events, followed by weak events like SN 1986G, followed by about 90% of all SNe Ia which are called "normals," to the stronger than normal events like SN 1991T.

The luminosity function of SNe Ia declines very steeply on the bright side (*e.g.* Vaughan *et al.* 1995). Since selection effects cannot prevent the discovery of SNe which are brighter than the "normals," this means that the normal SNe Ia are essentially the brightest.

(4) Fairly young populations appear to be most efficient at producing SNe Ia (tend to be associated with spiral arms in spirals; Della Valle & Livio 1994; Bartunov *et al.* 1994), but an old population ($\tau \gtrsim 4 \times 10^9$ yr) *can also* produce them (SNe Ia occur in ellipticals; Turatto, Cappellaro & Benetti 1994). The

explosion strength appears to be inversely correlated with the age of the stellar population (Ruiz-Lapuente *et al.* 1995b).

As a consequence of the above points, and in particular the fact that SNe Ia are found also in elliptical galaxies, which shows that SNe Ia cannot be produced by core collapse of massive stars, the currently accepted model for SNe Ia is that they represent *thermonuclear disruptions of mass accreting white dwarfs* (WDs). Thus, the basic ingredient of the model for SNe Ia is the same type of object that is present in cataclysmic variables (CVs) and in supersoft X-ray sources (SSS). The question that needs to be answered is: which binary system or systems are the immediate progenitors of SNe Ia. Before I address this question, I would like to explain the importance of identifying the progenitors.

2 Why is the Identification of the Progenitors of SNe Ia Important?

Identifying the progenitor systems of SNe Ia is important for the following main reasons:

(i) In the absence of agreed upon detailed models for the explosion itself, a knowledge of the initial conditions and of the distribution of material in the vicinity of the exploding star are essential for the understanding of the explosion.

(ii) An identification of the progenitors will help (through the knowledge of the SNe Ia rate) to put constraints on models for binary systems evolution. In particular, it may help constrain the value of the common envelope efficiency parameter α_{CE} (see *e.g.* Iben & Livio 1993; Livio 1995; for reviews), which is presently very poorly known.

(iii) Galaxy evolution depends on the input from supernovae in terms of energy (radiative and kinetic) and nucleosynthetic products and on the evolution of the SN rate with time.

(iv) The use of SNe Ia to determine H_o and q_o requires a knowledge of the evolution of the rate and the luminosity function of SNe Ia with cosmic time. Both of these quantities depend on the nature of the progenitors.

3 Constraints on the Basic Model

The basic model (thermonuclear disruption of an accreting WD) for SNe Ia can be further constrained. In particular, a combination of observations and theoretical calculations can be used in attempts to determine the required composition of the accreting white dwarf and the location in the WD (*e.g.* center vs. shell) and the fuel where ignition first occurs.

3.1 The Composition of the Accreting WD

The accreting WD could be, in principle of He, C-O or O-Ne-Mg composition. However, in the case of a He WD, the composition of the ejected matter would be primarily He and ^{56}Ni, which is inconsistent with the observations (see § 1). In the case of O-Ne-Mg WDs there is no *direct* observational argument which can exclude them as potential progenitors. Theoretical calculations show, however, that the frequency of events that can be expected from such accretors is not high enough to explain the observed (rather deduced) SNe Ia rate (*e.g.* Livio 1993). Furthermore, detailed calculations show that accreting O-Ne-Mg WDs tend more to collapse quietly to form neutron stars, rather than to explode as SNe Ia (*e.g.* Gutierrez *et al.* 1995).

Consequently, it appears most likely that *the accreting WDs that produce SNe Ia are of a C-O composition.*

3.2 Where in the WD and in which Fuel Does Ignition Take Place?

There are presently two classes of models being considered, one in which *carbon* ignites at the WD *center*, when the WD reaches the *Chandrasekhar mass* and the second, in which the accreted layer of *helium* ($\lesssim 0.2 M_\odot$) on top a C-O WD, ignites *off-center* typically at *sub-Chandrasekhar* masses. In the case of the carbon ignitors, numerical simulations have shown that the energetics, light-curve and composition as a function of ejection velocity are all generally quite consistent with observations, although some difficulties remain for the standard models (*e.g.* to produce rise times to blue maximum longer than 15 days; Branch *et al.* 1985; Harkness 1991; Höflich *et al.* 1995; Höflich *et al.* 1996). The fact that these models always explode at the Chandrasekhar mass has always been regarded as a potential explanation for the homogeneity of SNe Ia. The main difficulty at present with this class of models is related to statistics. Namely, it is not yet clear whether WDs in sufficient numbers to explain the SNe Ia rate can reach the Chandrasekhar mass (hydrogen and helium flashes which lead to mass loss make this difficult). A second, related difficulty, lies in the fact that WDs that are initially more massive than $1.2 M_\odot$ (and therefore more likely, perhaps, to reach the Chandrasekhar mass), tend to quietly collapse to form neutron stars rather than to explode (Nomoto & Kondo 1991), although it is presently not clear how firm this result is.

The helium (sub-Chandrasekhar) ignitors may produce (in principle) three different outcomes, two of which are certainly not normal SNe Ia. In the case of the "direct double detonation" (DDD) (namely, one detonation wave propagating outward through the helium and the second inward, through the C-O), the whole WD is burned into ^{56}Ni and He (Nomoto 1982; Woosley, Weaver & Taam 1980). This is inconsistent with the observation of high-velocity intermediate mass elements.

The "single detonation" (SD) case (the helium detonates but the C-O core does not), in which the core may survive as a WD or disintegrate at low velocities, certainly does not correspond to normal SNe Ia (Nomoto 1982; Woosley, Taam & Weaver 1986).

The only sub-Chandrasekhar model which has some chance to produce an explosion resembling a SN Ia is the "indirect double detonation" (IDD) model.

In this scenario, one detonation propagates outward through the helium, while an inward moving pressure wave results in ignition at the center (through the compression of the core), followed by an outward moving detonation (Livne & Glasner 1990; Woosley & Weaver 1994; Livne & Arnett 1995; Höflich & Khokhlov 1996).

Models of this type have been shown to produce light curves which are in agreement with those observed in SNe Ia. The main problems currently still existing with this model are: (1) The highest velocity ejecta have the wrong composition (^{56}Ni and He; *e.g.* Livne & Arnett 1995), this is due to the fact that in these models the intermediate mass elements have a He/Ni rich layer on top. Also, Si is generally absent (*e.g.* Höflich *et al.* 1996). (2) The light curve rises somewhat faster than observed (due to ^{56}Ni heating) and the early colors are inconsistent with observations (Höflich & Khokhlov 1996), (3) One might expect this model to produce a gradual decline on the bright side of the luminosity function, in contradiction to the observed sharp decline. The last point would have been a consequence of the range of WD masses that the IDD model allows (more massive WDs produce brighter SNe). It should be noted, however, that according to Pinto (private communication), their IDDs can produce excellent fits to both the light curves and the spectra.

As a consequence of the above discussion I feel that *carbon ignitors (at the Chandrasekhar mass) are presently favored by the observations*, but that the uncertainties that still exist in the calculations of the helium ignitor IDD models suggest that this model should still be considered.

4 Candidate Progenitor Systems

We now return to the question of which binary systems could be the immediate progenitors of SNe Ia. Branch *et al.* (1995) examined this question in detail using realization frequencies of SNe Ia obtained from a variety of binaries. The calculations were performed with a population synthesis code of the type used by Yungelson *et al.* (1994, 1996). Of the many uncertainties which are involved in these calculations two are by far the most important ones in terms of their effects on the final results: the efficiency parameter in common envelope evolution, α_{CE}, and the fraction η of the accreted mass, which a WD is able to retain. The efficiency parameter α_{CE} describes the fraction of the gravitational energy change due to spiralling-in inside the common envelope which is deposited into envelope ejection. Since other sources of energy (*e.g.* recombination energy) may be involved, α_{CE} could in principle be even larger than 1 (see Iben & Livio 1993; Livio 1995 for reviews). At present, possible values of α_{CE} are not reliably constrained neither observationally nor theoretically, although the most recent theoretical calculation seems to indicate a value $\alpha_{CE} \simeq 1$ (Rasio & Livio 1996). A similar uncertainty exists in relation to the accumulation ratio η. Different numerical codes result in rather different fractions of the accreted mass which remains atop the WD following shell flashes (*e.g.* Starrfield *et al.* 1992; Prialnik

& Shara 1995). Furthermore, the accumulation ratio in a combination of hydrogen and helium flashes is even less certain (*e.g.* Iben & Tutukov 1994; Kato, Saio & Hachisu 1989).

Acknowledging the fact that these (and other) uncertainties exist, Branch *et al.* (1995) adopted the following conservative assumption. A class of objects is *not* considered a major contributor to the SNe Ia rate, if the realization frequencies for young and old populations (respectively) satisfy: $\nu(\sim 10^8$ yr$) < 10^{-4}$ yr^{-1}, $\nu(\lesssim 10^{10}$ yr$) < 10^{-5}$ yr^{-1}. In Table 1 I give the realization frequencies for all the relevant candidate progenitors for carbon and helium ignitors as obtained by Yungelson *et al.* (1994, 1996). As can be seen from the table, if one insists on only *one class* of progenitors, then only WD mergers have a sufficiently high predicted frequency among the carbon ignitors. No single class can in fact produce the necessary frequencies among the helium ignitors, although symbiotic systems come close. I would like, however, to make the following comment. In some sense, the permanent supersoft X-ray sources represent what we have always been searching for in SNe Ia progenitors. Namely, WDs that burn steadily, and are therefore capable of growing in mass. We should therefore be very careful before we dismiss this class of potential progenitors on the basis of realization frequencies alone. In fact, the potential of producing the long sought for SNe Ia progenitors gives this class, in my mind, its main importance. The main families which contribute to the supersoft X-ray sources are marked in Table 1 by SSS.

I will therefore examine now in some detail these three classes of objects (merging WDs, symbiotics, supersoft X-ray sources).

WD mergers have been originally suggested as SNe Ia progenitors by Iben & Tutukov (1984) and Webbink (1984). Recent hydrodynamic calculations have shown that when the lighter of the two WDs fills its Roche lobe (the two WDs having been brought together by gravitational radiation), it is totally dissipated within a few orbital periods, to form a thick disk-type configuration (rotationally supported) around the primary (Rasio & Shapiro 1994; Benz *et al.* 1990). The subsequent evolution of the system is not entirely clear, since it is not known if central or off-center ignition (which may lead to an accretion induced collapse) will occur (*e.g.* Mochkovitch & Livio 1989, 1990; Mochkovitch *et al.* 1996). Two points which may give some confidence in the realization frequencies obtained for mergers are: (i) The population synthesis calculations indicate that for populations younger than $\sim 10^{8.5}$ yr, the total (combined) mass of the merging WDs is of order $2.1 M_\odot$, while it converges to the Chandrasekhar mass for older populations (Tutukov & Yungelson 1995). This may be consistent with the inverse correlation found between explosion strength and population age (Ruiz-Lapuente *et al.* 1995b). (ii) All the recently discovered double WD systems (Marsh 1995; Marsh, Dhillon & Duck 1995) fall into the peak of the period distribution predicted by the population synthesis calculations of Yungelson, Livio, Tutukov & Saffer (1994). On the other hand, it should be realized that some of the paths which lead to the formation of double WD systems involve *two* common envelope phases and thus they are necessarily uncertain (see *e.g.* Livio 1994).

Table 1. Candidate progenitor systems and their realization frequencies

Type of System	Realization Frequency for Young ($\sim 10^8$ yr) Population	Realization Frequency for Old ($\lesssim 10^{10}$ yr) Population
	a. Carbon Ignitors	
Cataclysmic Variable; SSS	2×10^{-5}	—
WD accreting from Roche lobe filling subgiant or giant; SSS	10^{-5}	10^{-6}
Symbiotic System; SSS	10^{-6}	10^{-4}
Helium CV	10^{-4}	—
WD accreting helium from Roche lobe filling giant	10^{-5}	—
Merger of CO + He WDs	10^{-4}	10^{-5}
Merger of CO +CO WDs	10^{-3}	10^{-4}
	b. Helium Ignitors	
WD accreting from Roche lobe filling subgiant or giant; SSS ?	—	3×10^{-4}
Symbiotic System; SSS ?	10^{-5}	10^{-3}
Helium CV	10^{-3}	—
Merger of CO + He WDs, or accretion from He WD	?	?

It is important to note that what has been considered until recently as a fatal difficulty for the merger scenario, the tentative detection of hydrogen in the supernova 1990M (Polcaro & Viotti 1991), probably poses no longer a problem, since this detection has been shown to be probably related to absorption in the parent galaxy rather than to the supernova environment (Della Valle, private communication). A difficulty that still exists is statistical in nature; among the 9 double WD systems discovered so far (Saffer, Liebert & Olszewski 1988; Bragaglia *et al.* 1990; Marsh, Dhillon & Duck 1995; Marsh 1995) not a single one is a SN Ia progenitor candidate, either because the orbital period is too long for the two WDs to merge in a Hubble time, or because the total mass is significantly lower than the Chandrasekhar mass. Other searches for double WD systems have given rather negative results (*e.g.* Robinson & Shafter 1987; Foss, Wade & Green 1991). While Yungelson *et al.* (1994) have shown that the results of any single one of these searches are still not in conflict with the possibility of producing SNe Ia at a rate compatible with observations ($\sim 3 \times 10^{-3}$ yr^{-1}), the combined negative results of all the searches starts to place uncomfortable constraints on this scenario (see also Renzini 1995).

As noted above, if helium ignitors represent the correct model (which presently appears difficult to accept), then symbiotic systems come the closest to producing the required frequency of SNe Ia. A real observational test for this scenario can come from deep radio observations performed immediately after the explosion. Due to the high wind mass loss rates observed from the giants in symbiotic systems ($\dot{M}_w \sim 10^{-6} M_\odot$ yr^{-1}), the circumstellar density in the vicinity of these systems should be high enough to produce detectable radio emission shortly after the SN explosion. Boffi & Branch (1995) showed that for $\dot{M}_w \sim 10^{-6} M_\odot$ yr^{-1}, the peak of the emission should occur about a week after the explosion and the expected peak flux is about 30 mJy (for a distance of 4 Mpc). Thus, the upper limit to the radio flux from (the rather weak) SN 1986G (Eck *et al.* 1995), appears to indicate that the progenitor of this supernova at least, is probably not a symbiotic system.

Finally, persistent supersoft X-ray sources, which involve a WD accreting at a rate $\gtrsim 10^{-7} M_\odot$ yr^{-1} from a subgiant companion (van den Heuvel *et al.* 1992; Rappaport, Di Stefano & Smith 1994; Yungelson *et al.* 1996) and burning hydrogen stably, include (in principle) the necessary ingredients for a system to reach the Chandrasekhar mass.

However, detailed population synthesis calculations (Yungelson *et al.* 1996) show that the realization frequencies that are obtained are rather low. This is a consequence of both the detailed history of the mass transfer process (steady burning occurs only in some episodes, while in others, nova outbursts lead to mass ejection) and of helium shell flashes, which lead to the loss of the accumulated helium shell. The rates at which the WDs reach the Chandrasekhar mass for the three families which are the main contributors to the supersoft X-ray sources population are: (i) in CVs, $2.2 \times 10^{-5} yr^{-1}$; in systems with subgiant donors, $0.6 \times 10^{-5} yr^{-1}$ and in systems in which a giant transfers helium via Roche lobe oberflow, $0.7 \times 10^{-5} yr^{-1}$. Thus the total rate, $3.5 \times 10^{-5} yr^{-1}$, is still considerably lower than the observed (rather deduced) one, $\sim 3 \times 10^{-3} yr^{-1}$. It should be noted, that while the rate at which IDDs (from helium ignitors) can (in principle) be obtained from supersoft sources is much closer to the observed SNe Ia rate (see Tab. 1), a detailed inspection of the evolution of these systems shows that most of the mass is accreted at rates that are too high ($\gtrsim 10^{-7} M_\odot yr^{-1}$) to produce successful IDDs (requiring a few $\times 10^{-8} M_\odot yr^{-1}$; Woosley & Weaver 1994).

Ultimately, the real test concerning the viability of supersoft sources (and symbiotic stars) as SNe Ia progenitors may rely on the presence or absence of hydrogen in emission in late time spectra. The point is, that hydrogen ablated from the subgiant donor is expected to end up on the inside of the SN Ia, expanding at low velocities, 200–2000 km s^{-1} (Chagai 1986; Livne *et al.* 1992). This is due to the fact that the subgiant is first engulfed by the expanding supernova envelope.

5 Conclusions

The following tentative conclusions can be drawn from the discussion presented in this paper.
(1) SNe Ia are *thermonuclear disruptions* of a *mass accreting C-O white dwarf.*
(2) It is not entirely clear yet if carbon is ignited first (in the center), when the white dwarf reaches the Chandrasekhar mass, or if helium is ignited first (off-center), at masses that are lower than the Chandrasekhar mass. Carbon ignition at the Chandrasekhar mass appears presently to be more consistent with observations.
(3) The immediate progenitors of SNe Ia are still unknown. The present "best bets" are: (i) the mergers of binary WDs, which can produce the required statistics, but maybe they lead to accretion induced collapses, rather than to SNe Ia. (ii) The persistent supersoft X-ray sources, which contain the necessary physical ingredients, but appear not to produce the required statistics. However, it is possible that some changes in our understanding of the physics of the mass transfer process (*e.g.* changes in the critical mass ratio which can still produce stable mass transfer; Hachisu, these proceedings) or of mass accumulation, will result in an increased realization frequency.

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Luminous Supersoft X-Ray Sources as Progenitors of Type Ia Supernovae

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Abstract. In some luminous supersoft X-ray sources, hydrogen accretes onto the surface of a white dwarf at rates more-or-less compatible with steady nuclear burning. The white dwarfs in these systems therefore have a good chance to grow in mass. Here we review what is known about the rate of Type Ia supernovae that may be associated with SSSs. Observable consequences of the conjecture that SSSs can be progenitors of Type Ia supernovae are also discussed.

1 Introduction

1.1 The Quest for Type Ia Supernovae and Their Progenitors

Type Ia supernovae can provide important clues about the age and evolution of the Universe. Several searches expected to significantly increase the discovery rate of Type Ia supernovae are underway (see, e.g., Leibundgut et al. 1995, and Perlmutter et al. 1995). The goal of the searches is to use these bright events to measure cosmological parameters, particularly the Hubble constant, H_0, and the deceleration parameter, q_0. The success of these programs depends upon having a good understanding of the characteristics of Type Ia supernova explosions. Of particular interest is the extent to which the maximum flux, light curve profile, and spectral characteristics are uniform among Type Ia supernovae, and the ability to quantify variations. To this end, an understanding of the progenitor systems and of variations among progenitors would be important. Yet the fundamental nature of the progenitors remains mysterious. We don't even know whether the progenitors are all of one type, or whether there may be several different types of progenitor. Livio (1996) has provided us with a comprehensive review of progenitor models. Other recent reviews include those by Wheeler (1996) and Branch et al. 1995.

1.2 Luminous Supersoft X-Ray Sources as Type Ia Progenitors

Rappaport, Di Stefano, & Smith (RDS; 1994) proposed that close-binary supersoft sources (CBSSs) might be Type Ia progenitors. They found that reliable calculations of the rate of Type Ia supernovae that might be associated with CBSSs required a much better understanding of the evolution of the systems than was available at the time. To derive a first estimate they assumed (1) a constant accretion rate, (2) conservative mass transfer, and (3) that the total mass of the white dwarf needed to grow to $1.4 M_\odot$ for a supernova to occur. If it was further assumed that the accretion rate needed to be within the range of rates compatible with steady burning throughout the evolution, the computed rate was less than a tenth of that required. On the other hand, relaxing this condition could yield rates in the requisite range. Thus, although conclusive results were not obtained, the possibility was open that CBSSs could contribute substantially to the rate of Type Ia supernovae. Yungelson et al. (YLTTF; 1996) took a somewhat different approach, and derived supernova rates compatible with the lower limits computed by RDS, as did Canal, Ruiz-Lapuente, & Burkert 1996. Although YLTTF did follow the complete evolution of some systems, neither their calculations nor those of RDS addressed the fundamental problems that prevented a first principle evolution to be carried out for many CBSSs.

Furthermore, neither investigation treated Roche-lobe-filling systems in which the donor was very evolved at the start of mass transfer. Such systems can have mass transfer rates in or near the steady nuclear burning region. Whereas for CBSSs, rates of this magnitude are driven by the thermal time-scale readjustment of the donor, when the donor is more evolved its nuclear evolution can push the mass transfer rate into the requisite region. We will refer to Roche-lobe-filling systems in which (1) $\dot{m}$ can be within the range for steady burning of hydrogen, and (2) the donor is initially more evolved than typical in CBSSs ($m_c(0) >\sim 0.2 M_\odot$), as wide-binary supersoft sources (WBSSs). The appearance of such systems will depend on the mass transfer rate, the mass ejection rate, and on the optical depth profile. They may or may not have the observational characteristics of SSSs or of symbiotics. Whatever the observational signature, WBSSs are characterized by the state of the donor, and the fact that there is an epoch, while the donor fills its Roche lobe, during which the mass transfer rate will allow for the more-or-less steady burning of hydrogen. The systems originally proposed by Whelan and Iben (1973) as Type Ia supernova progenitors, as well as those considered by Hachisu, Kato and Nomoto (HKN; 1996) are subsets of WBSSs.

Di Stefano et al. (DNLWR; 1996) reviewed some of the uncertainties faced in computing the rate of supernovae predicted by the close-binary supersoft model, and began to study the role of mass ejection. Similar work is ongoing for the wide-binary supersoft model (Di Stefano 1996a). This paper will focus on study of the close-binary supersoft sources; the paper by Di Stefano and Nelson (DN, 1996a) serves as a companion paper which includes much of the background touched on more lightly here. Before proceeding with the details of completed and ongoing work, however, it is worth taking a moment to review the context in which the work takes place.

1.3 Promise and Problems

Although white dwarfs that achieve the Chandrasekhar mass, M_C, have long been thought to be progenitors of Type Ia supernovae, viable progenitor models have not been easy to devise. This, in spite of the fact that several varieties of accreting white dwarfs, especially cataclysmic variables (CVs) and symbiotics, have been the subject of intensive research during recent decades. In CVs, for example, the donor is typically a low mass star and, because the accretion rate is low, most or all of the mass it donates can be lost in hydrodynamic events associated with episodes of nuclear burning. The problem with symbiotics is different. Even though the donor may have enough mass to contribute in order to push the white dwarf over the Chandrasekhar limit, and even though the mass accretion rate can be compatible with steady nuclear burning, the mass transfer phase is generally too short-lived for most white dwarfs to reach $M_{\rm C}$ (Kenyon et al. 1993). Recently, Yungelson et al. (1995) showed that wind-driven symbiotics, in which the donor does not fill its Roche lobe, are likely to make only a negligible contribution to the rate of Type Ia supernovae if the white dwarf needs to achieve the Chandrasekhar mass in order for an explosion to occur.

Given these difficulties, it has been suggested that accreting white dwarfs may become Type Ia supernovae even if they do not reach $M_{\rm C}$ (see, e.g., Woosley and Weaver 1994). The critical circumstance may instead be the ability to accrete in such a way as to form a helium mantle of $\sim 0.1 - 0.2 M_\odot$ around a C-O white dwarf. There has been good deal of study and discussion about these sub-Chandrasekhar progenitor models in recent years, but a consensus on the likelihood that they constitute a large fraction of the observed Type Ia supernovae has not yet emerged. However, even if it would become clear that reaching the Chandrasekhar mass is not an absolute requirement, this might not much change the rate of supernovae associated with some of the accreting white dwarf models. For example, Yungelson et al. (1995) found that, even if the accretion of as little as $0.1 M_\odot$ could lead to a supernova, symbiotics can account for at most 1/3 of the rate inferred from observations.

It was against this backdrop that luminous supersoft X-ray sources burst onto the scene. CBSSs seem, on the face of it to be perfect candidates for Type Ia supernova progenitors. A significant fraction of the donors are massive enough that they could donate sufficient mass to help their white dwarf companion achieve $M_{\rm C}$. And the mass transfer rates can be within the range required for steady nuclear burning. Thus, the white dwarfs can genuinely increase in mass. Although the candidacy of CBSSs thus sounds promising, there are problems as well. In fact, the very features that allow the mass transfer rate to be high enough to be compatible with steady nuclear burning, the fact that the donor may be more massive and also slightly evolved, also makes the candidacy of CBSSs as Type Ia supernova progenitors somewhat problematic. This is because these same features tend to be associated with unstable mass transfer, so that many of the candidate systems risk a common envelope that would likely end the phase of steady accretion onto the white dwarf.

In this paper we will not be able to resolve the uncertainties. Instead we will attempt to clearly delineate them and the steps (both in rate computations and other tests of SSS models) that can be taken to narrow them.

2 Defining the Relevant Rates

It is important to clearly delineate the physical processes whose rates we would like to compute. The first hypothesis we would like to test is that the evolution of SSSs can lead to a rate of Chandrasekhar-mass explosions consistent with the rate of observed Type Ia supernovae. In this scenario, a C-O white dwarf accretes hydrogen from a companion in either a close-binary supersoft source (CBSS) or a wide-binary supersoft source (WBSS). The hydrogen burns to helium, but is likely to burn through to heavier elements before a helium mantle can develop. Thus, if the white dwarf started with an initial mass less than $\sim 1.2 M_\odot$, we are likely to witness a "classic" Chandrasekhar-mass Type Ia supernova explosion of a C-O white dwarf.

A second hypothesis we would like to test is that SSSs could lead to sub-Chandrasekhar-mass explosions. Presumably, this would require that a significant helium mantle would be able to develop, and may therefore be unlikely. Nevertheless we keep track of the numbers of systems in which the white dwarf accretes as much as $\sim 0.2 M_\odot$.

A third hypothesis, is that the explosions are actually triggered in CBSSs and WBSSs in which the binary evolution breaks down, and a common envelope ensues, leading to the merger of the white dwarf with the core of the donor. If the donor has a helium core at the time the common envelope commences, then the merger might lead to something like a sub-Chandrasekhar explosion. If, however, the donor has a C-O core (as could be the case for WBSSs), then the merger process could possibly produce a composite object with mass greater than or equal to M_C.

In practice, we find that events of all three types are associated with the evolution of CBSSs and WBSSs. It is the computation of the relative rate that is complicated by difficulties in computing the fraction of CBSSs and WBSSs that can survive as viable mass transfer binaries without experiencing a common envelope. It is interesting to note, however, that whatever the eventual breakdown of the relative rates, all of these types of events are predicted by the SSS models and should be observed.

3 Recent Work

3.1 Quantifying the Problems

As discussed by DN, the condition that the donor continuously fill its Roche lobe, together with the conservation of angular momentum, leads to an equation for $\dot{m}$, the mass loss rate of the donor of the following generic form.

$$\dot{m}\mathcal{D} = \mathcal{N} \tag{1}$$

$\mathcal{D}$ has a functional dependence on β, which is itself a function $\dot{m}$. Thus, equation (1) can be viewed as a non-linear equation for $\dot{m}$. There are problems with stability when $\mathcal{D}$ passes through zero and/or is negative. In general $\mathcal{D}$ can be written as $\mathcal{A} + \beta\mathcal{B}$. If $\mathcal{D}$ is negative for all $\beta > 0$, we will say that the system is in class I; systems in class I cannot be evolved using the standard formalism. A system will be said to be in Class II if there is a value of $\beta = \beta_{crit}$, such that $\mathcal{D}$ is positive only for $\beta < \beta_{crit}$; the evolution of systems in class II can be started, but will fail as the rate of mass transfer increases, if β becomes equal to or exceeds β_{crit}. A system will be said to be in Class III if $\mathcal{D}$ is positive for all values of $\beta < 1$; systems in class III can be evolved from start to finish.

Using as input the systems that emerge as CBSS candidates from the population synthesis study of RDS, DNLWR found the following statistics. (1) Across a range of assumptions about the properties of primordial binaries and the value of α, the common envelope ejection factor, the rate at which CBSS candidate systems are formed in a galaxy such as our own is $\sim 0.5 - 1.0$ per century. This is just $\sim 2 - 3$ times as large as the rate of Type Ia supernovae inferred from observations. The rate at which WBSS candidates are formed is more sensitive to input assumptions about α, but can be comparable to the CBSS formation rate. (2) Across the same range of assumptions, we found that between $45 - 72\%$ of all CBSS systems were in class I and therefore could not be evolved. Between $10 - 20\%$ of all systems were in class II; their evolution crashed sometime after beginning, generally as the system approached the steady nuclear burning region. Between $17 - 36\%$ of all systems were in class III and could therefore be fully evolved. The story these statistics tell is somewhat more damning than may be obvious at first, since the systems in class III typically either have a mass ratio, $q = m/M$ (where m is the mass of the donor and M is the mass of the white dwarf), that is small (i.e., not much greater than unity), or else contain donors that are not very evolved. The associated mass transfer rates therefore tend to be small; the system does not spend much time in the steady nuclear burning region, and the white dwarf does not grow significantly. Thus, even though (and in some sense because) systems in class III can be followed, they tend not to be good candidates even for sub-Chandrasekhar Type Ia supernovae. Table 1 illustrates the range of results we obtained.

3.2 The Role of Mass Ejection

Table 1 illustrates two important features. First, for the population synthesis study of RDS, the majority of systems cannot be evolved using the standard formalism; they would seem to be candidates for a phase of common envelope evolution and possible mergers. Second, if the retention factor, β can be small–i.e., if the white dwarf can eject incident material it cannot burn, then a large enough fraction of systems may survive as viable binaries, to allow CBSSs to account for a significant fraction of either Chandrasekhar-mass or sub-Chandrasekhar-mass explosions. This is the point illustrated by the last row of the table, in which an "optimistic" treatment was used: all systems for which $\mathcal{D}$ was less than zero, were artificially saved, until the system parameters changed enough to increase $\mathcal{D}$ above zero. This treatment is not realistic and was designed to give us an

Table 1. Classification of CBSS candidates by retention-factor

		ΔM $\geq$ **0.2** Class I	Class II	Class III		
1	CON	0.72	0.10	0.18	**0.012**	**0.10**
2	CON	0.67	0.12	0.21	**0.009**	**0.02**
3	CON	0.73	0.10	0.17	**0.012**	**0.10**
4	CON	0.53	0.15	0.32	**0.015**	**0.16**
5	CON	0.51	0.18	0.31	**0.016**	**0.14**
6	CON	0.45	0.20	0.36	**0.018**	**0.18**
6	OPT	0.45	0.20	0.36	**0.55**	**0.81**

Summary of the results of evolutionary calculations. "Set" refers to the data sets of CBSS candidates that emerge from each of 6 population synthesis studies we have carried out along the lines described in RDS. Note that there is relatively little variation among the results derived for different data sets. "Case" refers to the class of evolutionary "treatment" used to evolve the CBSS candidates. There are two classes of treatment, conservative (CON) and optimum (OPT). The numbers in each column represent the average fraction of systems that fall into the category indicated by the column headings. A treatment is characterized by the values of the parameters used in the evolution of the CBSS candidates. These include a_1 and a_2 (see DN), and the value of $\tilde{\xi}_{ad}$. In rows $1-6$, the average of the results for 9 separate conservative treatments is shown. In our standard conservative treatment, $\tilde{\xi}_{ad}=4$, $a_1=2$, and $a_2=1$. Although the results for individual treatments are not shown, we note that the results among the conservative treatments are not generally dramatically different for different treatments. The exception is for $\tilde{\xi}_{ad}=10$. This case tends to maximize the value of $\mathcal{D}$, so that all systems can be evolved; we find however, that the mass transfer rates tend to be so low that no system reaches $1.4M_\odot$. In row 7, the results for the optimum treatment, which has been applied here only to data set 6, are shown. The evolutionary parameters are the same as those for the standard conservative treatment; when $\mathcal{D}<0$, however, β is chosen so as to set $\mathcal{D}$ equal to $\mathcal{D}_{min}$. Note that all systems in Class I and some in Class II are candidates for mergers.

upper limit. The fact that the upper limit so-derived is in the range of observed rates, illustrates the significant role played by mass ejection in the computation of the Type Ia supernovae rates.

It has since been discovered (HKN) that there are steady state solutions in which the white dwarf can eject the matter that it cannot burn. This is a potentially important result. Together with several other steps, it should help us to better quantify the Type Ia supernovae rate associated with SSSs. The additional needed developments include the following. (1) A population synthesis study which differs from that of RDS in including the effects of winds prior to the first common envelope phase. This has already been done by YLTTF, and by DN. The results are to move some systems from class I into class II. (2) The inclusion of radiation-driven winds. This allows us to evolve some systems in class II that would otherwise fail. We find, though, that this by itself does not lead to a significant increase in the number of systems in which the white dwarf accretes $\sim 0.2 M_\odot$ or more. (3) Implementing the full non-linear solution to Equation (1). This will allow us to better determine which systems in class II can actually be saved (Di Stefano 1996a). (4) Explicitly including a common envelope phase for those systems in which the binary evolution fails. This will allow us to better quantify the number of merger events expected. (5) Completing a full population synthesis study, including evolution, for wide-binary supersoft sources.

Work along these lines is underway and should help us to narrow the uncertainties in computations of the rate of Type Ia supernovae associated with luminous supersoft X-ray sources.

4 Predictions and Tests of the Model

A promising coincidence of computed and observed rates would not be conclusive evidence that the model is the unique correct Type Ia progenitor model. What would be needed in addition are testable physical predictions that go beyond rate computations. In this section we focus on two types of test. The first is the identification of individual progenitors, and the second is *post facto* study of supernovae and their remnants for "secondary characteristics" (Branch et al. 1995) that may be related to properties of the progenitor.

4.1 Searching for Progenitors

One way to definitively identify progenitors is to observe a system before it experiences an explosion. The problem with this approach is the events are rare. To date, no Type Ia supernova progenitors have been identified. If the rate of events is ~ 0.3 per century per galaxy, we would need to have detailed prior information about ~ 30 galaxies to have a good chance of identifying a progenitor sometime in the next decade. To test the supersoft source progenitor models we therefore ask if the distinctive signatures of SSSs would help us to identify the site of a progenitor in a distant galaxy.

X-Ray Observations As part of the study of the detectability of SSSs, Di Stefano & Rappaport (1994) seeded the Magellanic Clouds and M31 with SSSs drawn from a distribution generated by using the CBSS model. Because steady nuclear burning white dwarfs of higher mass tend to be hotter and more luminous, we found that the sources most likely to be detected in M31 were those with high-mass white dwarfs. This is illustrated in Figure 1.

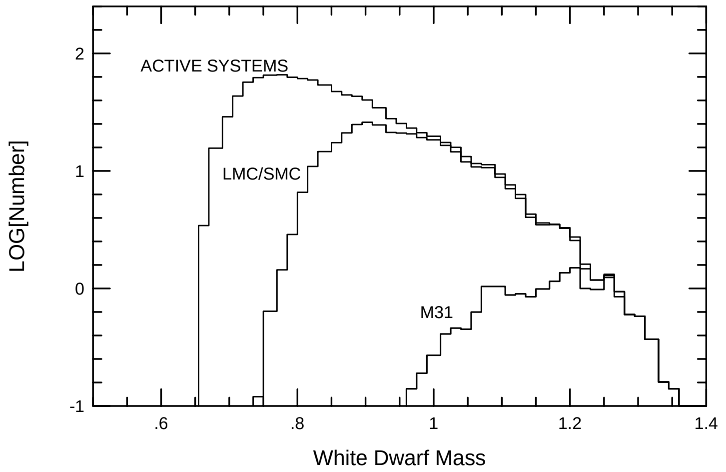

Fig. 1. The uppermost curve represents all active CBSSs as calculated by RDS. The middle (low) curve shows only systems that would likely have been detected by ROSAT in the LMC/SMC (M31).

Note that ROSAT's study of M31 should have detected evidence of all steady nuclear burners with $M > 1.2 M_\odot$ (see Greiner et al. 1996, Supper et al 1995). An important caveat is that the system should not be self-obscured, by a heavy wind, for example. This selection effect, favoring X-ray detection of systems with high-mass white dwarfs, becomes more pronounced as the distance to the host galaxy and/or absorption increases. Deep images of the most distant galaxies in which sources can be detected and resolved by X-ray satellites would therefore seem to provide potentially promising ways to identify possible progenitors. This is especially true if the Chandrasekhar-mass models are correct.

Observations of Supersoft Nebulae The radiation emitted by SSSs is highly ionizing. If the sources are housed in an ISM with a local number density, n, of more than $\sim 1-2$ cm^{-3}, they may be expected to exhibit an ionization nebula with high enough surface brightness to be detected, and with distinctive properties (Rappaport et al. 1994; Chiang 1996). The central source is capable of maintaining the ionization of $\mathcal{O}(100) M_\odot$, with, for example, $\sim 2-8\%$ of the bolometric luminosity emerging in the $\lambda 5007$ line of [O III]. We will refer to these distinctive nebulae as supersoft nebulae. CAL 83 is associated with a nebula that fits the general expectations computed for a supersoft nebula (Pakull and Motch 1989; Remillard, Rappaport and Macri 1995 [RRM]). At the detection limit of RRM, no other SSS in the Magellanic Clouds exhibits such a nebula. It is unknown what fraction (1) of the sources discovered to date, and (2) of all active SSSs, may be associated with supersoft nebulae.

Di Stefano, Paerels, and Rappaport (1995; DPR) noted that at least some supersoft nebulae should have luminosities in [O III] $\lambda 5007$ comparable to the cut-off of the planetary nebula luminosity function (PNLF) (see Fig. 2).

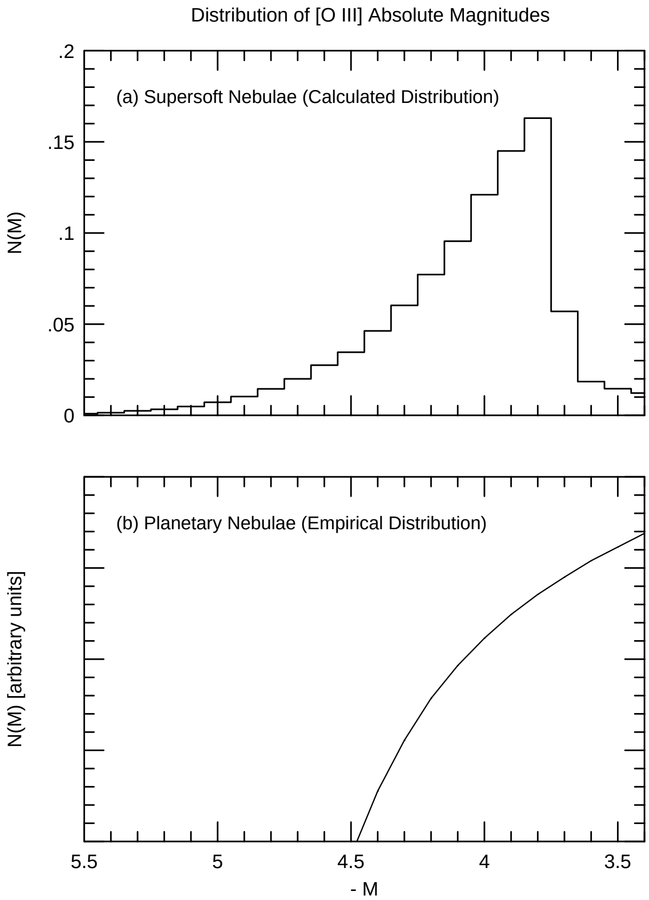

Fig. 2. The top panel shows the supersoft nebula luminosity function (SNLF) in [O III]. The normalization is not known; if, e.g., 10% of all SSSs have supersoft nebulae, then a total of $\mathcal{O}(100)$ supersoft nebulae may be expected to exist in a galaxy such as our own. The bottom panel shows the empirically-derived planetary nebula luminosity function (PNLF).

The PNLF is used to determine extragalactic distances (see, e.g., Jacoby et al. 1992, Jacoby and Ciardullo 1993). Comparison between the SNLF and the PNLF therefore indicates that, if there are significant numbers of supersoft nebulae in distant galaxies, we should be able to detect individual SSSs in galaxies at least as far from us as the Virgo cluster. Planetary nebula surveys have been and are continuing to be carried out for dozens of galaxies. Thus, there is some chance that a coincidence between the location of a nebula and the site of a later Type Ia supernova explosion could be observed during the next decade, if SSSs can be progenitors of Type Ia supernovae (Di Stefano 1996b). Features which can help to distinguish between supersoft nebulae and planetary nebulae have been considered by DPR. It is interesting to note that supersoft nebulae are more

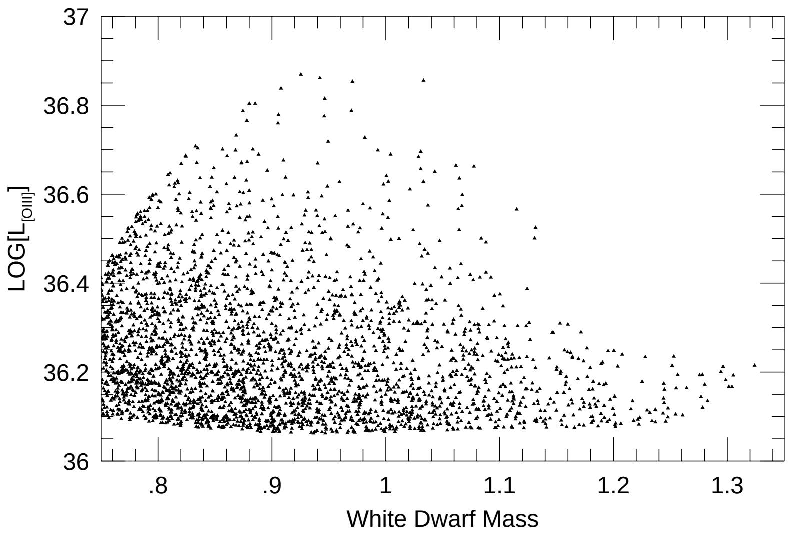

Fig. 3. The distribution of [O III] luminosities as a function of white dwarf mass. (Di Stefano 1996b)

efficient emitters in the [O III] line when the temperature of the central source is moderate, and the mass of the white dwarf is smaller than $1.2 M_{\odot}$. This is illustrated in Fig. 3.

Thus, while X-ray detection of SSSs in external galaxies is most likely to test and constrain Chandrasekhar-mass models, detection of supersoft nebulae in distant galaxies is most likely to test and constrain sub-Chandrasekhar-mass models.

4.2 Predicting Supernova Characteristics

Observational work that may allow us to eventually identify individual progenitors is exciting, but the returns are necessarily uncertain. On the other hand, we know that ongoing search programs for supernovae will certainly lead to the study of dozens of Type Ia supernovae during the next decade. Thus, if a set of tests to be applied to each observed explosion could be devised to assess the likelihood that the progenitor was a SSS, we might have a better chance of verifying or falsifying the hypothesis that SSSs are the progenitors of a significant fraction of Type Ia supernova explosions.

Branch et al. 1995 discussed a range of so-called "secondary characteristics" of supernovae that could be used to constrain progenitor models. For example, the amount and distribution of circumstellar matter can be checked via radio observations. (See, e.g., Boffi & Branch 1995, Eck et al. 1995.) Evolutionary calculations allow us to compute the total amount of mass ejected by each system and to follow the time history of mass ejection. In ongoing work, both for wide- and close-binary systems, we are therefore tracking mass ejection. Our calculations also allow us to compute the ionization state of any local ISM (as well as that of ejected material) prior to the explosion; post-explosion limits on these quantities are also possible to obtain (see, e.g., Kirshner, Winkler & Chevalier 1987, and Smith et al. 1991).

5 Conclusions

The possibility that supersoft sources are progenitors of Type Ia supernovae is intriguing. There are many hurdles to be gotten over, however, before we can properly assess the situation.

One small hurdle has already been passed. That is, we have established that the pool of close-binary supersoft sources and wide-binary supersoft sources is large enough that, should a substantial fraction of the systems lead to supernovae, the rate of explosions could be comparable to the rate inferred from observations. This result emerges in a straightforward way from population synthesis analyses. It is interesting that the rate at which candidate progenitors are formed is, in most of our simulations, just a few times larger than the required rate. Thus, if less than 0.1 of the candidates could become supernovae, the rate of explosions due to SSSs would constitute only a small fraction of the requisite rate.

The main hurdle, then, is to determine what fraction of the candidates are actually supernova progenitors. This is a difficult problem. Solving it requires making advances in the study of the binary evolution of systems in which a more massive and possibly quite evolved star donates mass to a white dwarf companion. It seems possible that recent and ongoing work may help us to determine the fraction of candidate systems that can survive as viable binaries in which the white dwarf accretes significant mass. Even the binaries that do experience common envelopes are interesting, and determining the rates of all possible outcomes is therefore important.

Whatever the outcome of the rate calculations, the ability to evolve individual systems allows us to compute some features of the post-explosion system related to the total amount of mass ejected or to the state of ionization. Such calculations may help us to constrain the SSS models for Type Ia supernova progenitors. Further, X-ray and nebular observations of galaxies may eventually provide complementary constraints on the progenitor models.

In summary, the status of SSSs as progenitors of Type Ia supernovae is still uncertain. But there are clear lines of investigation that should help us to narrow the uncertainties.

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A New Model for Progenitors of Type Ia Supernovae and Its Relation to Supersoft X-Ray Sources

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Abstract. We propose a new model for progenitors of Type Ia supernovae and discuss its relation to super soft x-ray sources. The model consists of an accreting white dwarf and a lobe-filling, mass-losing low mass red giant. When the mass accretion rate exceeds a critical value, 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 of the mass-losing star to 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 which is limited to $\dot{M}_{\rm cr} = 9.0 \times 10^{-7} (M_{\rm WD}/M_\odot - 0.50) M_\odot$ yr^{-1}, and the rest is blown off by wind. The photospheric temperature is kept around $T \sim 1 \times 10^5 - 2 \times 10^5$ 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 so that it can grow 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 star may not be observed during the strong wind phase due to self-absorption by wind itself. Strong winds stop when the mass transfer rate decreases below $\dot{M}_{\rm cr}$. Then, it can be observed as a supersoft x-ray source.

1 Introduction

Observations and models strongly indicate that Type Ia supernovae (SNe Ia) are thermonuclear explosions of accreting white dwarfs. 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; Branch et al. 1995 for recent reviews). Though these white dwarf models more or less can account for various observational aspects of SNe Ia, the exact binary evolution that leads to SNe Ia has not been identified. Different evolutionary scenarios have been proposed, neither of them positively proven yet. They include: 1) a double degenerate scenario (DD), i.e., merging of double C+O white dwarfs with a combined mass surpassing the Chandrasekhar 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 vs. sub-Ch* and *DD vs. 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 discovered only several systems whose combined mass is less than the Chandrasekhar mass (Branch et al. 1995; Renzini 1996 for reviews). Theoretically, the DD has been suggested to lead to accretion-induced-collapse rather than SNe 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 thus concluded that the SD/sub-Ch combination scores better than the SD/Ch and DD/Ch combinations.

However, photometric and spectroscopic features of SNe Ia are better reproduced by the Ch model than the sub-Ch 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 propose a new progenitor model for SNe Ia. Our scenario may also account for why the number of the observed DD is significantly less than the predictions by Iben & Tutukov 1984; Webbink 1984.

In the scenario of Iben & Tutukov 1984 and Webbink 1984, they excluded a close binary system consisting of a mass-accreting white dwarf and a lobe-filling, mass-losing red(sub)-giant, mainly because such a system suffers from unstable mass transfer when the mass ratio of the mass-accreting white dwarf to the mass-losing red giant 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 of $\log T$ (K) ~ 5.2 (Iglesias et al. 1987; Iglesias et al. 1990; Iglesias & Rogers 1991; Iglesias & Rogers 1993; Rogers & Iglesias 1992). This peak in the new opacity is about three times larger than that of the Los Alamos opacity (Cox & Stewart 1970a; Cox & Stewart 1970b; Cox et al. 1973]). Such a large enhancement of the new opacity certainly drives a strong wind on the mass-accreting white dwarf, 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 it 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 $M_{\rm WD,0} = 0.8 - 1.2 M_\odot$ and a low-mass red(sub)-giant star with $M_{\rm RG,0} = 0.8 - 1.5 M_\odot$ having a helium core of mass $M_{\rm He} = 0.2 - 0.4 M_\odot$. This assumption is consistent with the fact that SNe Ia appear everywhere in spiral galaxies and even in elliptical galaxies (e.g., Tammann 1982; Cappellaro & Turatto 1988). We have followed binary evolution of these systems by using an empirical formulae and obtained the parameter range which 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 companion to the white dwarf. If a steady mass transfer is realized, its rate is given by

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

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

$$H(q) = \left(\frac{2}{3} - \frac{0.4q^{2/3} + q^{1/3}/3(1+q^{1/3})}{0.6q^{2/3} + \ln(1+q^{1/3})}\right)(1+q) - 2(1-q), \tag{2}$$

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 white dwarf component, and M_2 the mass of the secondary, i.e., the low-mass star component). Here we use the empirical formula proposed by Eggleton 1983 as an effective radius of the inner critical Roche lobe. To estimate $(\dot{R}_2/R_2)_{\rm EV}$ we use the empirical formulae proposed by Webbink et al. 1983:

$$\left(\frac{\dot{R}_2}{R_2}\right)_{\rm EV} = \left(c_1 + 2c_2 y + 3c_3 y^2\right)\frac{\dot{M}_{\rm He}}{M_{\rm He}}, \tag{3}$$

where $y \equiv \ln(M_{\rm He}/0.25M_\odot)$ with the mass of the helium core $M_{\rm He}$. The increasing rate of the helium core mass is calculated by $\dot{M}_{\rm He} = L_2/X\varepsilon_H$, where L_2 is the luminosity of the secondary, X the hydrogen mass fraction, and $\varepsilon_H = 5.987\times10^{18}$ ergs g^{-1} the nuclear energy release per unit mass. 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 time scale but rather on a thermal or dynamical time scale. The gas falls very rapidly onto the white dwarf and forms an extended envelope around the white dwarf (e.g., Nomoto et al. 1979; Iben 1988). This envelope expands to eventually fill the inner and then outer critical Roche lobe. It results in the formation of a common envelope, in which the two cores are spiraling in each other. It forms a very compact binary system consisting of a C+O white dwarf and a helium white dwarf and never produces an SN Ia.

However, the recent version of the opacity changes the situation. In such a large mass accretion rate, hydrogen shell burning ignites soon after the envelope mass exceeds a critical value. Then, the nuclear burning dominates the compressional heating as a source of the luminosity. The luminosity is very close to the Eddington luminosity and, therefore, the envelope structure depends strongly on

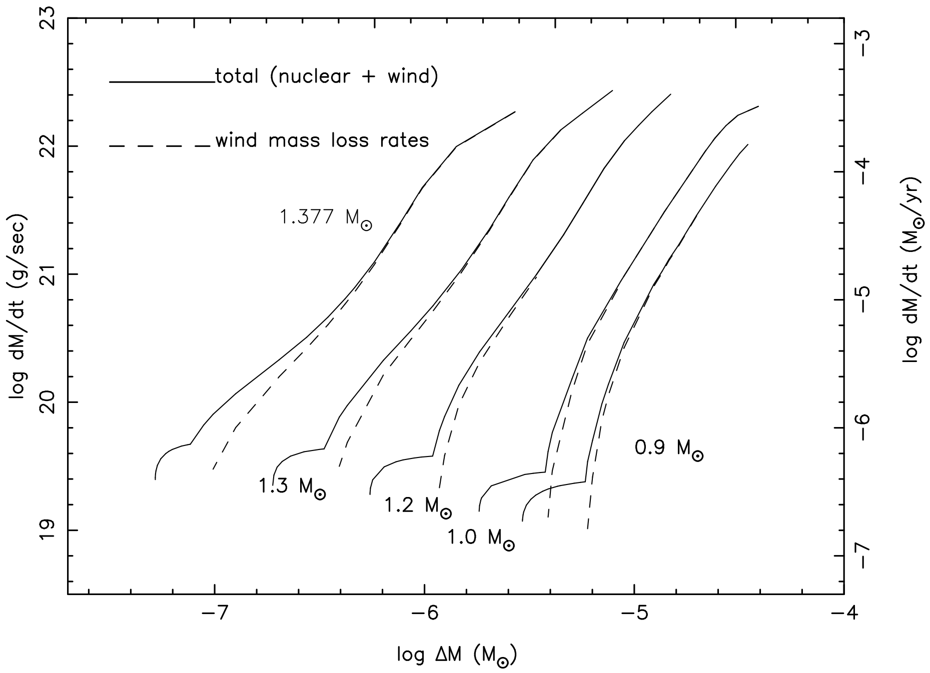

Fig. 1. Wind mass loss rates (dashed line) and total mass consumption rates, i.e., nuclear burning rates plus wind mass loss rates, are plotted against the envelope mass for white dwarfs with masses of 0.9, 1.0, 1.2, 1.3 and 1.377 $M_\odot$. The mass is attached to each line.

the opacity. The new opacity, OPAL opacity, has a very strong peak (three times larger than the old Los Alamos opacity) at $\log T$ (K) ~ 5.2 so that the luminosity easily exceeds the local Eddington luminosity if the photospheric temperature of the envelope is lower than $\sim 200,000$ K. It drives an optically thick wind. Optically thick wind is a continuum-radiation driven wind in which the acceleration occurs deep inside the photosphere. We have shown such solutions in Fig. 1. 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 white dwarf after it burns into helium. The total mass consumption rate (nuclear burning plus wind mass loss) is also plotted in the same figure. Here, we assume steady-state and spherical symmetry to calculate structures of mass-losing envelopes and implicitly assume that the white dwarf accretes matter from the equator and blows wind from the other area.

We also plot the relation between the photospheric temperature and the total mass consumption rate in Fig. 2. If the mass transfer rate is given, the wind mass loss rate is determined from Fig. 1 and the photospheric temperature is obtained from Fig. 2. It should be noted that the photospheric temperature is higher than $100,000$ K when the mass transfer rate is as small as or smaller than $\sim$

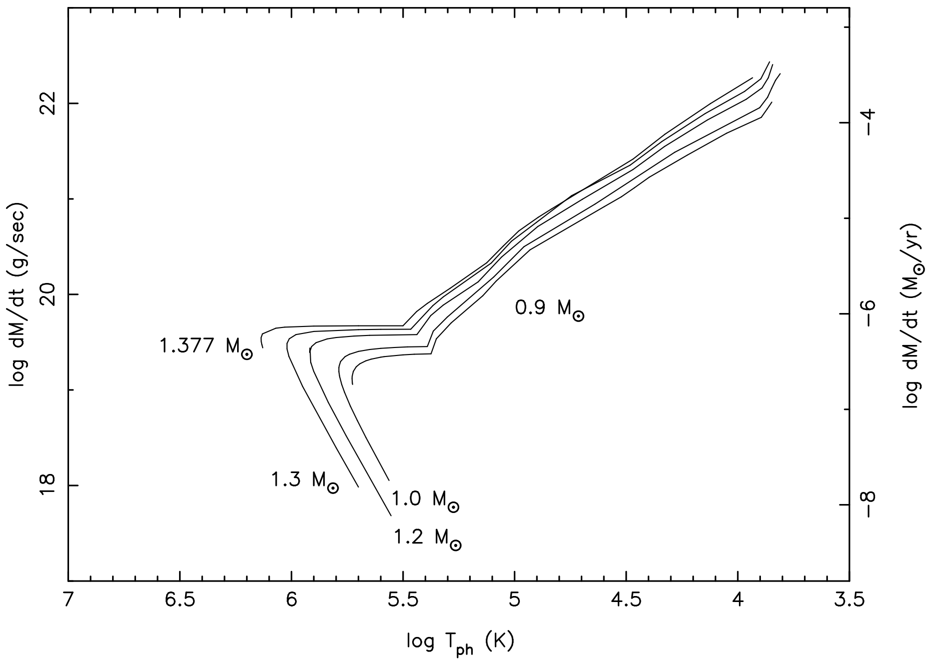

Fig. 2. Total mass consumption rate vs. photospheric temperature for white dwarfs with masses of 0.9, 1.0, 1.2, 1.3 and $1.377 M_{\odot}$.

$1 \times 10^{-5} M_{\odot}$ yr^{-1}. Even if the mass transfer rate is as large as $\sim 1 \times 10^{-4} M_{\odot}$ yr^{-1}, this optically thick wind is able to blow off the transferred matter. For such a high rate, the photospheric radius expands and the photospheric temperature decreases to $\sim 10,000$ K.

The wind velocity is about several hundred to one thousand km s^{-1} when the mass transfer rate is as small as or smaller than $\sim 1 \times 10^{-5} M_{\odot}$ yr^{-1}. For such a case, specific angular momentum of the wind is estimated as

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

$$\ell = \left(\frac{q}{1+q} \right)^2, \tag{5}$$

where J and M are the total angular momentum and the total mass of the system, respectively, and a the separation, $\Omega_{\rm orb}$ the orbital angular velocity. We assume a circular orbit. 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. This effect stabilizes the mass transfer. Which effect wins determines the stability of mass transfer. These effect of mass transfer can be expressed as

$$\frac{\dot{M}_2}{M_2} = \left(\left(\frac{\dot{R}_2}{R_2} \right)_{\rm EV} - H_1(q) \left(\frac{\dot{M}_1}{M_1} \right) \right) / H_2(q), \tag{6}$$

$$H_1(q) = -\frac{2}{3} + \frac{0.4q^{2/3} + q^{1/3}/3(1+q^{1/3})}{0.6q^{2/3} + \ln(1+q^{1/3})} + \frac{1}{1+q} - 2 + 2\ell \frac{1+q}{q}, \tag{7}$$

$$H_2(q) = \frac{2}{3} - \frac{0.4q^{2/3} + q^{1/3}/3(1+q^{1/3})}{0.6q^{2/3} + \ln(1+q^{1/3})} + \frac{q}{1+q} - 2 + 2\ell(1+q). \tag{8}$$

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

The white dwarf can accrete the processed matter at a rate of

$$\dot{M}_{\rm cr} = 9.0 \times 10^{-7} \left(\frac{M_{WD}}{M_\odot} - 0.50 \right) M_\odot \ {\rm yr}^{-1}, \tag{9}$$

during the strong wind phase as shown in Figs. 1 and 2. When the mass transfer rate decreases below this critical value, optically thick wind stops. If the mass transfer rate decreases further below $\sim 1.0 \times 10^{-7} M_\odot$ yr^{-1}, hydrogen shell burning becomes unstable to trigger a weak shell flash. In this paper, we simply assume that the white dwarf can accrete all the transferred matter until the mass transfer rate decreases below $0.5 \times 10^{-7} M_\odot$ yr^{-1}.

The system can be specified by three parameters, i.e., the initial white dwarf mass, $\mathrm{M_{WD,0}}$, the initial red giant mass, $\mathrm{M_{RG,0}}$, and the mass of the helium core of the red giant at the beginning of mass transfer, $\mathrm{M_{RG,0}(He)}$, (or, the separation of the binary, a_0). We have followed the evolution of these close binary systems for various sets of parameters. If the mass transfer rate becomes smaller than $0.5 \times 10^{-7} M_\odot$ yr^{-1} before the white dwarf reaches $1.38 M_\odot$, we regard that hydrogen shell flashes on the white dwarf blow off the accumulated matter and the white dwarf never grows any more. We simply assume that all the transferred matter can be processed and then accumulated on the white dwarf when the mass transfer rate is larger than $0.5 \times 10^{-7} M_\odot$ yr^{-1}. The example of such an evolution is plotted in Fig. 3. In this case, the white dwarf can grow up to $1.38 M_\odot$ to induce an SN Ia. The mass of hydrogen envelope on the white dwarf is $\sim 10^{-6} M_\odot$ (Fig. 1) at the explosion, which is too small to be observed. On the other hand, there still remains $\sim 0.1 M_\odot$ hydrogen in the red giant envelope and it may be observed as low velocity components of the H-alpha line. The final outcome of the evolution is summarized in Fig. 4 against these three parameters. The region to induce SN Ia is smaller for smaller $M_{\rm RG,0}(\rm He)$.

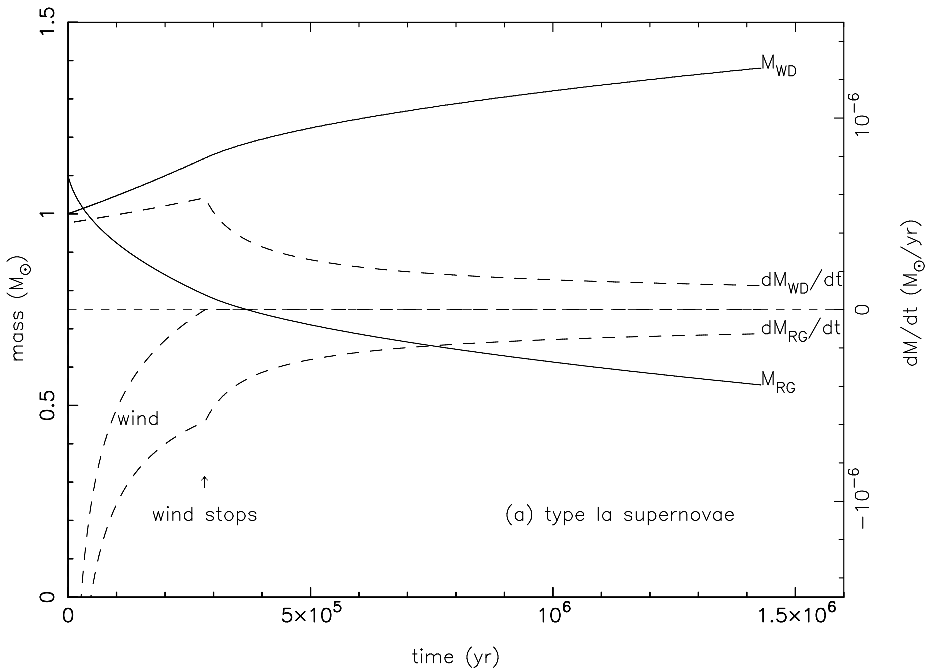

Fig. 3. Time evolution of the system. (a) The white dwarf increases its mass through $1.38 M_\odot$ and explodes as a SN Ia. Solid lines denote the masses of the white dwarf and the red giant companion, respectively. The dashed lines denote the net mass accumulation rate onto the white dwarf, the wind mass loss rate, and the mass transfer rate from the red giant component, respectively from top to bottom.

3 Discussion

The steady hydrogen shell burning converts hydrogen into helium atop the C+O core and increase the mass of the helium layer gradually. When its mass reaches a certain value, helium ignites. For the accretion rate given by equation (9), helium shell burning is unstable to grow to a flash. Once a helium shell flash occurs on relatively massive white dwarfs ($M_{WD} \gtrsim 1.2 M_\odot$), a part of the envelope mass is blown off due to wind mass loss (Kato et al. 1989); however, the ratio of the lost mass to the initial envelope mass is small (less than 10%). The total mass lost from the system would be smaller than 0.02 $M_\odot$.

The effective temperature of the accreting white dwarf is about $\sim 100,000 - 200,0000$ K during the strong wind phase. 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 (9), wind stops and the photospheric temperature quickly increases up to $\sim 1 \times 10^6$ K because its steep dependency on the mass transfer rate as shown in Fig. 2.

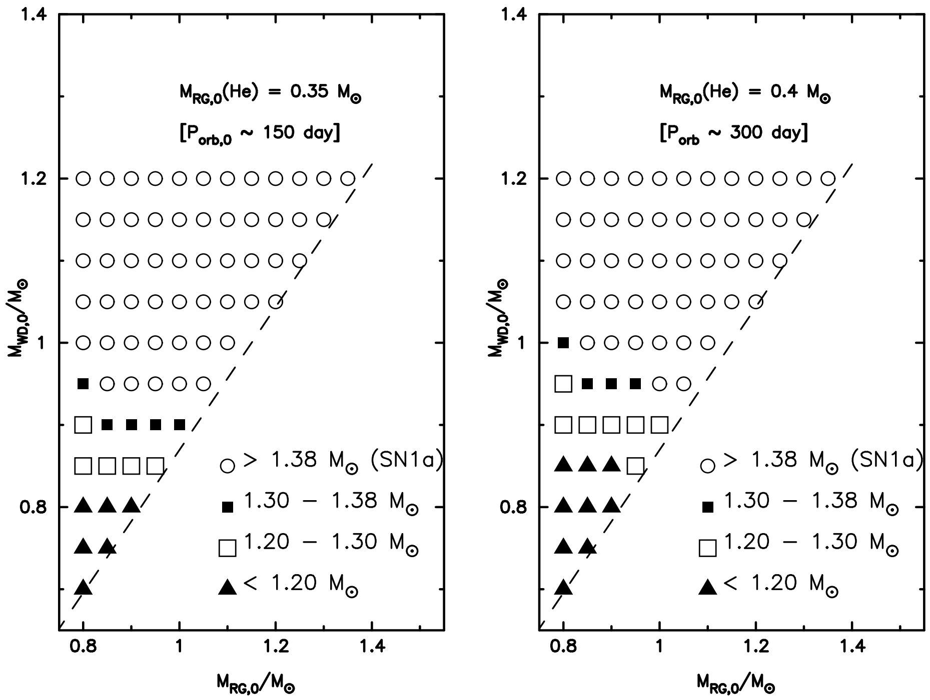

Fig. 4. Outcome of the evolution as a function of the initial mass of the white dwarf, the initial mass of the red giant, and the mass of the helium core at the beginning of mass transfer.

If we assume that $5-8\ M_\odot$ stars leave C+O white dwarfs larger than $0.9\ M_\odot$ (e.g., Weidemann & Koester 198; Iben & Tutukov 1985), the rate of SNe Ia coming through this route is close to the observed rate, i.e., $0.002\ \mathrm{yr}^{-1}$ in our Galaxy. Here, we have estimated the rate by using equation (1) of Iben & Tutukov 1984 and substituting $\Delta \log A = 1$, $q = 0.1 - 0.3$, $M_A = 8$, 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; 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 Case B mass transfer) if the mass transfer rate does not exceed much larger than $\sim 10^{-4} M_\odot\ \mathrm{yr}^{-1}$. This may resolve the discrepancy between the DD prediction and the DD observation mentioned above.

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Transient and Recurrent Supersoft Sources as Progenitors of Type Ia Supernovae and of Accretion Induced Collapse

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Abstract. Modeling the X-ray light curves of the transient supersoft X-ray sources RX J0045.4+4154 and RX J0513.9-6951 by recurrent shell flashes massive white dwarfs ($M_\odot \sim 1.33 - 1.38\ M_\odot$) accreting at high rates ($\gtrsim 0.1 - 3.\ 10^{-7}\ M_\odot\ yr^{-1}$) are found. These are candidate progenitors of accretion induced collapse (AIC). RX J0019.8+2156 and RX J0527.8-6954 can be considered to be candidate progenitors of SNe Ia.

1 Introduction

The final fate of accreting white dwarfs (WDs) in binary systems is still a question of debate and of detailed theoretical investigations. The most recent calculations spanning a wide parameter range have been presented by Prialnik and Kovetz, 1995. These calculations clearly show that depending on the masses, mass accretion rates and the thermal history (temperature) of the WDs different final fates result: erosion, growth, destruction by an explosion or collapse. The last two events may lead to a type Ia supernova (SN Ia) and an accretion induced collapse (AIC) respectively. The specific conditions which have to apply are at least in part fulfilled in the new and distinct class of supersoft sources established after the extensive *ROSAT* observations (cf. for a review of the observations Hasinger, 1994; Kahabka & Trümper, 1996 and for detailed population synthesis calculations van den Heuvel et al., 1992; Rappaport, Di Stefano & Smith, 1994; Di Stefano & Rappaport, 1994; Yungelson et al., 1996). The aim of this article is to present the present state of knowledge about the properties of supersoft binaries being interesting as possible progenitors for SN Ia and for the AIC. Although the methods used to infer system parameters may be of concern and the parameters themselves may be highly uncertain, such an approach seems to be justified in order to initiate a first direct comparison with predictions from population synthesis calculations. The large uncertainties inherent in the numbers of existent and predicted supersoft binary systems and the still existent uncertainty in the rate of SNe Ia (and the AIC) allow only a qualitative comparison of numbers and rates. It is not the aim of this article to solve any kind of discrepancies. As the observed numbers of identified (or highly probable) binary supersoft sources per host galaxy (Milky Way, LMC, SMC, and M31) are extremely small ($\sim$ 7,5,3, and 1) such an attempt would lack any reliability.

2 Classification Scheme for Supersoft Sources

After optical identifications have been achieved for a large fraction of the supersoft sources discovered with the *ROSAT* and the *EINSTEIN* satellite it became clear they do not form a homogeneous class but comprise several source classes. In this section a classification scheme is set up and in section 3 it is investigated which sources are candidate progenitors of SNe Ia and of AIC. One classification is according to the nature of the companion star, a main-sequence star, a slightly evolved star in or slightly above the main-sequence (subgiant), or a lower mass red giant star. Another classification is in terms of the mass transfer ($\dot{\rm M}$) properties in these binary systems. Steady-state nuclear burning (with the hydrogen being converted into helium at about the same rate as it is accreted) has been predicted to occurr only within a narrow range of mass transfer rates ($\sim 1-4 \times 10^{-7}\ M_{\odot}\ yr^{-1}$) for WD masses in the range $0.7-1.2$ $\mathrm{M}_{\odot}$. Below that rate nuclear burning happens in weak flashes and at still lower rates in strong flashes or even in an explosive event (a nova outburst). Yungelson et al., 1996 proposed to term these classes CV-type, subgiant and symbiotic (donor properties). They proposed a sub-classification into permanent and recurrent sources which would relate to their mass transfer properties. Systems accreting slightly above the stability band of steady nuclear burning and undergoing cyclic (time variable) accretion (cf. Pakull et al. 1993) may constitute an additional sub-class. Class identifiers M,S,G and sub-class identifiers p,c,r are defined in Table 1.

This classification scheme has been applied to the observed supersoft sources which are binaries. From a sample of 26 classical novae only two objects have been found as supersoft sources, Nova Mus 1983 and Nova Cyg 1992 (Ögelman et al. 1993; Krautter et al. 1996). They are found below the CV period gap of ~2-3 hours. Two additional supersoft sources 1E 0035.4-7230 and RX J0439.8-6809 with orbital periods in the range of ~3-4 hours (Schmidtke et al., 1996a, 1996b) are supposed to have main-sequence star donors and possibly lower mass white dwarfs. These possible novae are not considered to be likely candidates for SNe Ia. Three symbiotic systems RR Tel (Jordan et al. 1994), AG Dra (Greiner et al. 1996) and SMC3 (Jordan et al. 1996) are supersoft sources. They are possibly all symbiotic novae. The nature of the donor star is not always very conclusive although it has been proposed to be a giant of spectral type G to M.

Table 1. The classification scheme of supersoft sources.

Component	Class definition	Abbrev.
Donor	Main-sequence star (in part red dwarf dK to dM)	M
	Evolved main- or post main-sequence star (subgiant)	S
	Giant (of low mass $\sim 1-3\ M_{\odot}$)	G
White dwarf	Steady-state burning sources (persistent)	p
	Cyclic accretion (passing above the stability band)	c
	Unstable burning (mild flashes) sources (recurrent)	r

Table 2. Optically identified supersoft binary systems (with possibly evolved main-sequence stars or post main-sequence stars) which are candidate progenitors of SNe Ia and of AIC.

Name	P_{orb}[d]	Ref.
CAL 87	0.442	1-3
RX J0019.8+2156	0.660	4-6
RX J0513.9–6951	0.76	7-12
CAL 83	1.04	1,13-14
RX J0925.7-4758	3.8	15,16

Ref.: (1) Long et al. 1981; (2) Pakull et al. 1988; (3) Schmidtke et al. 1993; (4) Beuermann et al. 1995; (5) Greiner & Wenzel 1995; (6) Gänsicke et al. 1996; (7) Schaeidt et al. 1993; (8) Pakull et al. 1993; (9) Cowley et al. 1993; (10) Cowley et al. 1996; (11) Crampton et al. 1996; (12) Reinsch et al. 1996; (13) Smale et al. 1988; (14) Greiner et al. 1991; (15) Motch et al 1994; (16) Motch 1996. CAL 83

3 Transient and Recurrent Sources

A large fraction of the supersoft sources varies in X-rays with time. The origin of variability on shorter time scales (hours) may be connected to the binary orbit (cf. Kahabka 1996a); the longer time scales have been proposed to be related to unstable nuclear burning at accretion rates slightly below the steady-state burning rate (Kahabka 1995) or to cyclic accretion at rates exceeding temporary the stability limit (Pakull et al. 1993). In Fig. 1 we show the *ROSAT PSPC* X-ray light curves of two transient supersoft sources. For the transient RX J0045.4+4154 in M31 two X-ray outbursts have been detected (White et al. 1995). The LMC transient RX J0513.9-6951 has been discovered in the *ROSAT* all-sky survey during an X-ray outburst and two additional outbursts have been detected during a monitoring campaign (Schaeidt et al. 1993; Schaeidt 1996; Reinsch et al. 1996).

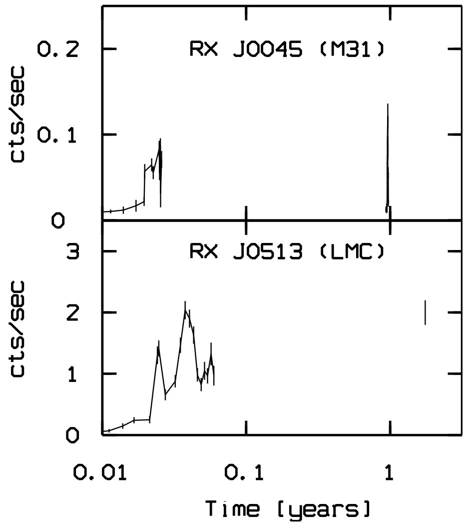


Fig. 1. *ROSAT PSPC* X-ray light curves of the cyclic accreting supersoft source RX J0513.9-6951 in the LMC and the recurrent supersoft source in M31.

3.1 Recurrent Shell Flashes

Unstable nuclear burning has e.g. been modeled in the work of Prialnik and Kovetz, 1995 using hydrodynamic calculations. They derive a gid of models covering the parameter space of supersoft sources (in terms of white dwarf mass, temperature, and mass accretion rate). The envelope masses they derive (critical masses M_{acc}) at the onset of the outburst can be represented in an analytical form by (cf. Kahabka, 1995)

$$\log M_{acc} = 3.532 + 1.654\,(M_{WD})^{-1.581} \ln(1.4 - M_{WD}), \tag{1}$$

for an accretion rate of $\dot{M} = 10^{-7} M_{\odot} yr^{-1}$ and with the mass of the white dwarf M_{WD}. The observables *outburst recurrence time* t_{recur} and *x-ray on-time* t_{on} can be related to the critical envelope mass

$$M_{env}^{crit} = M_{acc} - M_{env}^{min} = \dot{M}_{stable} \times t_{on}(1 - \frac{t_{on}}{t_{recur}}) \tag{2}$$

with the minimum envelope mass for which nuclear burning can be sustained M_{env}^{min}. In this approach large primary masses ($1.0 - 1.4\ M_{\odot}$) and high mass transfer rates ($\sim 8 \times 10^{-8} - 4 \times 10^{-7}\ M_{\odot}\ yr^{-1}$) have been derived for the transients (cf. Table 3). In Figure 2 the distributions of white dwarf masses and mass accretion rates deduced with the approach of recurrent nuclear burning are shown. From hydrodynamic calculations Prialnik & Kovetz, 1995 derived e.g. the recurrence period of outbursts for a grid of white dwarf masses, temperatures and mass accretion rates. The result is given in Fig. 3. Applying to RX J0513.9–6951 with a recurrence period of ∼100-200 days derived from the optical light curve with the *MACHO* project (Alcock et al. 1995) and a very large mass accretion rate close to $\sim 10^{-6}\ M_{\odot} yr^{-1}$ (Southwell et al. 1996) a white dwarf mass of $\sim 1.3\ M_{\odot}$ is obtained. This may mean the source experiences a weak flash during the outburst which results in an envelope expansion without ejection. A strong wind mass loss phase may follow the envelope expansion phase. After the envelope has been consumed by wind mass loss and in part by nuclear burning the hot nuclear burning white dwarf is reveiled. This pattern repeats.

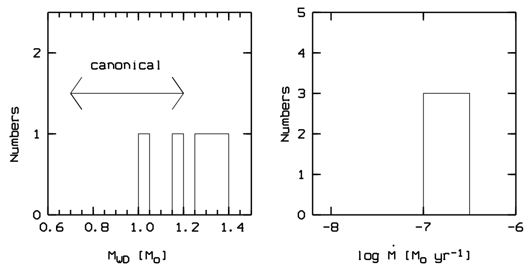
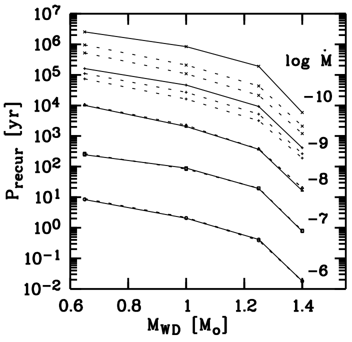


Fig. 2. Distribution of white dwarf masses and effective mass accretion rates for transient supersoft sources in the model of recurrent shell flashes (cf. Kahabka 1995). The values are taken from Tab. 3 and are in part highly uncertain.



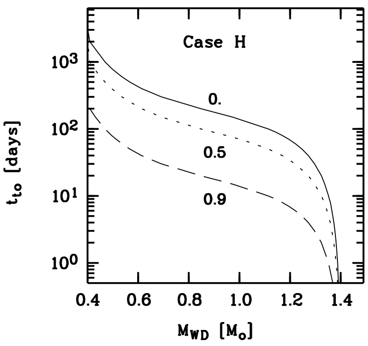


Fig. 3. Left panel: Recurrence period of outbursts (from Prialnik and Kovetz, 1995) as a function of the white dwarf mass M_{WD} and the mass accretion rate $\dot{M}$. Results are given for different temperatures of the white dwarf: 1.10^7 K (solid line), 3. and 5.10^7 K (dotted line). Right panel: X-ray turn-on time t_{to} for supersoft sources as a function of the white dwarf mass M_{WD} for case H (high mass accretion rate 10^{-7} $M_\odot$ yr^{-1}). A contracting envelope model is used. The solid, dotted and dashed curves refer to f_{loss} = 0, 0.5 and 0.9 respectively, the fraction of the envelope mass either ejected during the outburst or lost by a wind during the envelope contraction phase.

3.2 Cyclic Accretion at Rates Above the Stability Band

Another model has been proposed to account for the observed time variability on time scales of days to months, variable mass transfer onto massive white dwarfs (Pakull 1993, Southwell et al. 1996). In case cyclic (time variable) accretion is the correct model for a source (e.g. for RX J0513.9–6951), considerably larger (maximum) accretion rates are deduced than for systems accreting at rates below the stability band.

3.3 X-Ray Turn-Ons

An additional source of information are the observed X-ray turn-ons in several of the supersoft sources. These have been modeled as envelope contraction of the blown-up white dwarf following a nuclear flash (Nariai 1974, Kahabka 1996b). The observed turn-on time in X-rays t_{contr}^{obs} corresponds to a temperature change of the WD envelope from $\sim$ 1 to 5×10^5 K and is in this approach given by Equ. 3 assuming that a fraction f_{loss} of the mass in the envelope is either ejected during the outburst or lost during the contraction phase by a wind.

$$t_{contr}^{obs} \approx 1200(\frac{M_{env}(1 - f_{loss})}{10^{-4} M_\odot})(\frac{0.01 R_\odot}{R_{core}}) \text{ days.} \tag{3}$$

From Fig. 3 it becomes obvious that even if $\sim$ 90% of the envelope mass is lost (ejected) X-ray turn-on (contraction) time scales of $\approx$10 days afford very massive white dwarfs ($M_{WD} \gtrsim 1.2$ $M_\odot$). For a discussion of the effects of (optically thick) winds on nova outbursts and supersoft sources we refer to Kato & Hachisu, 1994

Table 3. Parameters of transient and recurrent supersoft sources which can be considered as candidate progenitors of SNe Ia (and of AIC). The mass of the white dwarf M_{WD} [$M_\odot$], mass accretion rate $\dot{M}_7$ [10^{-7} $M_\odot$ yr^{-1}], wind velocity v_W [km/sec], bolometric luminosity L[$L_\odot$] of the white dwarf, orbital period P_{orb} [d] and mass of the donor star M_d [$M_\odot$] is given. Values for the white dwarf masses enclosed in brackets are deduced from the X-ray turn-on times.

Galaxy	Source	WD				donor		Ref.
		M_{WD}	$\dot{M}_7$	v_W	log(L)	P_{orb}	M_d	
LMC	RX J0513.9-6951	(1.33-1.36)		~4000	3.5-4.1	0.76		1-4
	RX J0527.8-6954	≤ 1.18	≤ 1.6		2.0-3.9			1-2
Milky	RX J0925.7-4758	?	?			3.8		
Way	RX J0019.8+2156	0.97-1.10	1.2-2.6	~1000	~3.0	0.66	~1	6
M31	RX J0045.4+415	1.34-1.38	0.09-1.9					2,7
		(1.37-1.38)						4

Ref.: (1) Kahabka & Trümper 1996 (from van Teeseling et al. 1994; (2) Kahabka unpublished results (cf. Kahabka 1995); (3) Crampton et al. 1996; (4) Kahabka 1996b; (5) Jordan et al. 1996; (6) Beuermann et al. 1995; (7) White et al. 1995.

and Hachisu, Kato & Nomoto, 1996. Using for R_{core} a mass-radius relation (e.g. Nauenberg 1972) the dependence of t^{obs}_{contr} on the mass of the white dwarf M_{WD} is obtained. The result is shown in Fig. 3. This model allows to deduce independent estimates for the white dwarf masses, which turn out to be consistent with the masses deduced from the analysis of the recurrence behavior of the sources. A compilation of the system parameters deduced from this and other work is given in Tab. 3.

4 The Case for SNe Ia

The homogeneity of SNe Ia in terms of spectra, light curves and absolute peak luminosities (cf. Livio et al., 1995 and references therein) has been considered as indicator for a rather well confined class of progenitors, i.e. thermonuclear explosions of accreting C-O WDs. This comprises accreting WDs and WD mergers (with one component finally accreting from the other component disrupted into a He accretion disk). Several scenarios have been considered to lead to an explosion of the WD. The main two cases are (1) ignition of carbon at the center of the WD after it reaches the Chandrasekhar mass and (2) off-center detonation after conversion of $\lesssim 0.2$ $M_\odot$ of hydrogen accreted on top of a C-O WD into helium. The initial mass of the WD before the start of the accretion event should be below ~ 1.2 $M_\odot$ (excluding ONeMg WDs) in order to avoid a collapse. Case (1) has been considered to be most promising in explaining the observed characteristics of SNe Ia (cf. Branch et al., 1995). Case (2) may account for part of the smaller fraction of optically fainter SNe Ia events but specific (and highly uncertain) explosion scenarios have to be set up in order to get rough consistency within the observations (cf. Nomoto et al., 1984). For a discussion of sub-Chandrasekhar mass models for SNe Ia it is referred to Woosley and Weaver, 1994 and Canal, Ruiz-Lapuente and Burkert, 1996. Rappaport et al., 1994 derive from population synthesis calculations of steady supersoft binary sources SN Ia rates due to Chandrasekhar core collapse as high as $3-6\times10^{-3}$ yr^{-1} which are at the upper bound close to the upper limit of the observationally inferred galactic SN Ia rate of $\sim 3-7\times10^{-3}$ yr^{-1}. Yungelson et al., 1996 find from their population synthesis calculations a SN Ia rate for case (1) of $\sim 3.5\times10^{-5}$ yr^{-1}. This is well below the observed rate. For case (2) they derive a rate of $\sim 3\times10^{-4}$ yr^{-1}. The supersoft sources given in Table 3 can be considered to be good candidate progenitors of SNe Ia, the symbiotic novae may contain lower mass white dwarfs and may explode via channel (2).

5 The Case for AIC

WDs with masses in excess of ~ 1.2 M$_\odot$ before the onset of accretion (mostly ONeMg) may grow in mass for sufficiently high mass accretion rates and experience an Accretion Induced Collapse (AIC) if they reach the Chandrasekhar mass (cf. Isern & Hernanz, 1995). Yungelson et al., 1996 derive for the Milky Way a rate of permanent supersoft sources experiencing the AIC of $(3-4)\times10^{-5}$ yr^{-1}. As ~ 0.2 M$_\odot$ of the mass of the WD is removed by neutrino emission, neutron stars formed by this channel are expected to have masses of ~ 1.2 M$_\odot$. RX J0045.4+4154, a supersoft source in M31, can be considered to be a strong candidate for the AIC (Kahabka, 1995). Finally it should be noted that an independent way to derive an estimate of the SN Ia rate of a galaxy is by means of the nucleosynthesis products, the heavy element content (Tsujimoto et al. 1995).

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