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Li, X.D.; van den Heuvel, E.P.J.

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Letter to the Editor

Evolution of white dwarf binaries: supersoft X-ray sources and progenitors of type Ia supernovae

X.-D. Li[1,2] **and E.P.J. van den Heuvel**[1]

[1] Astronomical Institute, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[2] Department of Astronomy, Nanjing University, Nanjing 210093, P.R. China (email: lixd@crater.nju.edu.cn)

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Abstract. The discovery of supersoft X-ray sources, described as massive white dwarfs burning accreted matter from their (more massive) companions, opens a new channel to type Ia supernovae (SNe Ia). According to conventional binary evolutionary theory, if the mass ratio of the donor to the white dwarf exceeds a critical value, the mass transfer becomes unstable, and a common envelope will be formed. However, recent calculations by Hachisu, Kato & Nomoto (1996) suggest a strong wind to stabilize the mass transfer when the mass transfer rate is higher than a certain value. Adopting the strong wind assumption, we have performed evolutionary calculations of white dwarf binaries, in which mass transfer occurs through Roche-lobe overflow, to search for the progenitors of SNe Ia. We find that there are two types of systems that can produce SNe Ia. One is close binaries with ~ 2 to $\sim 3.5 M_\odot$ main-sequence or subgiant companions, and the initial orbital period of several tenth of a day to several days. The other is wide binaries with low-mass ($\sim 1 M_\odot$) red giant companions and long initial orbital period (tens to hundreds of days). The derived birth rate of SNe Ia in the Galaxy is roughly consistent with the observed one.

Key words: binaries: close – stars: mass loss – supernovae: general

1. Introduction

Supersoft X-ray sources (hereafter SSS), originally discovered with the *Einstein* satellite in the Large Magellanic Cloud (Long, Helfand & Grabelsky 1981), and more recently with *ROSAT* (Trümper et al. 1991), are a class of luminous (bolometric luminosity $\sim 10^{37} - 10^{38}$ erg s^{-1}) objects, with a characteristic radiation temperature of 30 to 60 eV. The number of known SSS exceeds 30, and their main properties have been reviewed by Hasinger (1994), Kahabka & Trümper (1996) and in the recent book edited by Greiner (1996).

The presently accepted interpretation of SSS is that they are binary systems containing massive white dwarfs ($M_{\rm WD} \sim 1 M_\odot$) which steadily burn nuclear fuel on their surface accreted from a ~ 1.5 to $\sim 3 M_\odot$ main-sequence or subgiant companion star at a rate near or above the Eddington limit (van den Heuvel et al. 1992). Because of the large white dwarf masses and the high mass accretion rates in SSS, a fraction of these objects could actually grow beyond the Chandrasekhar limit and undergo explosion or collapse. This opens the evolutionary perspective that SSS may be the long-sought progenitors of SNe Ia.

Detailed population studies for SSS have been made by Rappaport, Di Stefano & Smith (1994) and by Yungelson et al. (1996). Rappaport et al. (1994), assuming a constant mass transfer rate and a 100% efficient conversion of the accreted hydrogen into helium, found that close-binary supersoft sources (CBSS) may grow to the Chandrasekhar mass with a rate as high as ~ 0.006 yr^{-1} in the Galaxy. A lower estimate (3×10^{-5} yr^{-1}) of the SNe Ia rate was derived by Yungelson et al. (1996). Recently, a new model for progenitors of SNe Ia was proposed by Hachisu, Kato & Nomoto (1996). The model consists of a white dwarf and a lobe-filling red giant. Hachisu et al. found a new strong wind solution when the mass accretion rate exceeds a critical value. The strong winds stabilize the mass transfer, even though the mass ratio of the donor star to the white dwarf is larger than 0.79, in which case the mass transfer was conventionally thought to be unstable to form a common envelope (cf. Iben & Livio 1993 for a review). Thus the strong winds from the mass-accreting white dwarf change the stability condition and are able to open a new channel to SN Ia explosions.

Motivated by the work of Hachisu et al. (1996), we have performed evolutionary calculations of white dwarf binaries with a lobe-filling companion star. The aim of our work is to inves-

Send offprint requests to: X.-D. Li

tigate the distribution of the possible SN Ia progenitors, and to test whether such systems can produce SNe Ia with a rate compatible with the observations. In the next section we describe our main assumptions. The results and discussion are presented in section 3.

2. The model

We consider a C-O white dwarf accreting matter from a companion with solar chemical composition (X=0.7, Y=0.28, Z=0.02). For the outcome of the evolution, we only consider the Chandrasekhar-mass SN Ia explosion of the white dwarf with an initial mass less than $1.2M_{\odot}$. The companion star is assumed to be lobe-filling, and mass transfer occurs through Roche-lobe overflow. Detached systems like symbiotic stars, in which the companion star of the white dwarf loses mass via a wind, are not taken into account, due to the deficiency of massive white dwarfs among such systems, and hence the low frequency ($\sim 10^{-6}$ yr^{-1}) of SNe Ia (Yungelson et al. 1995).

The system can be specified by three parameters: the initial white dwarf mass $M_{\rm WD,\,0}$, the initial donor mass $M_{\rm d,\,0}$ and the orbital period $P_{\rm orb,\,0}$ at the beginning of mass transfer. We have followed the evolution of these binary systems for various sets of these parameters, using an updated version of the evolution code developed by Eggleton (1971).

Whether the white dwarf can grow in mass is determined by the "accumulation ratio" α, the fraction of the accreted hydrogen that converts into elements heavier than helium. The value of α is related to mass loss from the white dwarf during hydrogen and helium burning, i.e., $\alpha \equiv \alpha_{\rm H}\alpha_{\rm He}$, where $\alpha_{\rm H}$ and $\alpha_{\rm He}$ are the fraction of the transferred mass accumulated during hydrogen and helium burning, respectively.

It has been shown (e.g. Nomoto et al. 1979; Fujimoto 1982) that steady hydrogen burning on the white dwarf surface can occur when $\dot{M}_{\rm low} \lesssim \dot{M} \lesssim \dot{M}_{\rm up}$, where $\dot{M}$ is the mass transfer rate, $\dot{M}_{\rm up} \simeq 8.5 \times 10^{-7}(M_{\rm WD}/M_{\odot} - 0.52)\, M_{\odot}$ yr^{-1} and $\dot{M}_{\rm low} \simeq 0.4\dot{M}_{\rm up}$ (note that even in this stable burning situation, not all of the accreted hydrogen is available for burning, because some of it can be lost via a radiatively driven wind). As $\dot{M} < \dot{M}_{\rm low}$, hydrogen burning is unstable and occurs in flashes, in which part of the white dwarf envelope may be ejected. For the hydrogen accumulation ratio $\alpha_{\rm H}$, we have taken the following assumptions: (1) if $\dot{M} > \dot{M}_{\rm up}$, we adopt the strong wind solution by Hachisu et al. (1996), which allows burning of hydrogen into helium at a rate limited to $\dot{M}_{\rm up}$, the excess material being blown off in the wind, i.e., $\alpha_{\rm H} = \dot{M}_{\rm up}/\dot{M}$; (2) if $\dot{M} \leq \dot{M}_{\rm up}$, we fit the data of the accumulation ratio calculated by Prialnik & Kovetz (1995) for hydrogen burning and flashes (for each combination of $M_{\rm WD}$ and $\dot{M}$) with the following conditions: (i) when $\dot{M}$ declines below $3 \times 10^{-8} M_{\odot}$ yr^{-1}, a strong nova explosion is assumed to occur and no mass accumulates on the surface of the white dwarf, that is $\alpha_{\rm H} = 0$; (ii) when $\dot{M} = \dot{M}_{\rm up}$, $\alpha_{\rm H} = 1$.

The steady hydrogen burning converts hydrogen into helium on top of the C-O white dwarf, and increases the mass of the helium layer gradually. When its mass reaches a certain value, helium ignites. Helium shell burning is unstable if $\dot{M}_{\rm He} \lesssim 10^{-6} M_{\odot}$ yr^{-1}, and a flash grows, during which part of the envelope mass is blown off (Kato, Saio & Hachisu 1989). For the helium accumulation ratio $\alpha_{\rm He}$, we use the results given by Kato et al. (1989).

The evolution of the system is driven by the nuclear evolution of the donor star, and the change of the orbital angular momentum $J_{\rm orb}$ of the system mainly caused by wind mass loss from the white dwarf, which is assumed to leave the system carrying the specific orbital angular momentum of the white dwarf (the mass loss in the donor's wind is supposed to be negligible, but its effect on the change of $J_{\rm orb}$, i.e., magnetic braking, is included). In each time step, we numerically calculate the response of the donor radius and the Roche-lobe radius, the difference of which determines the mass transfer rate, to mass loss from the donor, and mass and angular momentum loss from the binary respectively (a semi-analytical method was adopted by Hachisu et al. 1996 and by Di Stefano and Nelson 1996). The wind decreases both the total mass and the orbital angular momentum of the binary, leading to increase and decrease of the orbital separation, respectively. Thus the stability of mass transfer and the secular evolution of the binary sensitively depends on the values of $\alpha_{\rm H}$, $\alpha_{\rm He}$ and the mass ratio. Generally we have two kinds of products: (1) $M_{\rm WD}$ grows to 1.4 $M_{\odot}$, producing a SN Ia; (2) the calculations are stopped before $M_{\rm WD}$ reaches $1.4M_{\odot}$ because $\dot{M}$ exceeds $\sim 10^{-4} M_{\odot}$ yr^{-1} at which there is no wind solution, or $\dot{M}$ declines below $3 \times 10^{-8} M_{\odot}$ yr^{-1}, at which a strong nova explosion is assumed to occur, or for a low-mass ($\lesssim 1.5M_{\odot}$) donor, the helium core mass reaches 0.46 $M_{\odot}$.

3. Results and discussion

An example of the calculated evolution ($M_{\rm WD,\,0} = 1.0M_{\odot}$, $M_{\rm d,\,0} = 2.5M_{\odot}$, $P_{\rm orb,\,0}$ = 1.6 d) is plotted in Fig. 1. In this case the white dwarf can grow to $1.4M_{\odot}$ to trigger a SN Ia. Despite of an initial mass ratio of 2.5, the mass transfer is stabilized by the strong wind, and maintains a rate around $10^{-6} M_{\odot}$ yr^{-1} during the whole evolution, i.e., nearly above the steady burning region. A large fraction ($\sim$ 70%) of the transferred matter is blown off in the wind. The orbital period decreases to $\sim$ 0.7 d and then increases before the white dwarf mass reaches $1.4M_{\odot}$.

A possible candidate that shows a similar evolutionary path as in Fig. 1 is the transient supersoft X-ray source RX J0513.9-6951 in the Large Magellanic Cloud (Schaeidt et al. 1993). Spectroscopy and photometry observations suggest that this 0.76 d source may be a massive ($\sim 1M_{\odot}$) white dwarf accreting at a high ($\sim 10^{-6} M_{\odot}$ yr^{-1}) rate from a more massive ($2 - 3M_{\odot}$) companion star (Alcock et al. 1996; Southwell et al. 1996). The bipolar outflows with high speed ($\sim$ 3800 km s^{-1}) (Cowley et al. 1996; Southwell et al. 1996) are clear evidence of strong wind during high accretion case. The final evolution of this source will probably lead to a SN Ia or accretion-induced collapse (Kahabka 1996).

Figure 2 presents another example of the evolution for $M_{\rm WD,\,0} = 1.2M_{\odot}$, $M_{\rm d,\,0} = 1M_{\odot}$, and $P_{\rm orb,\,0}$ = 300 d. The

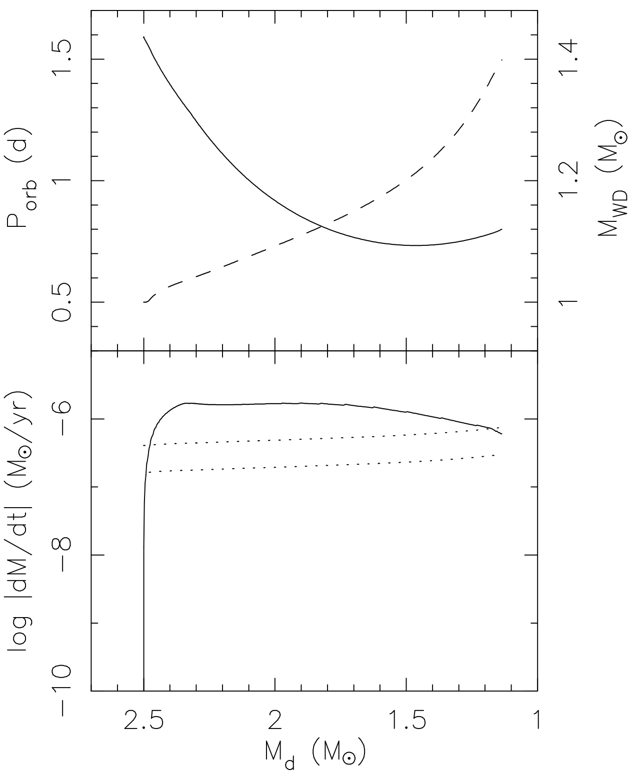

Fig. 1. Evolution of the white dwarf binary with $M_{\rm WD,0} = 1M_\odot$, $M_{\rm d,0} = 2.5M_\odot$ and $P_{\rm orb,0} = 1.6$ d. Upper panel: solid and dashed curves denote the evolution of the orbital period and the mass of the white dwarf, respectively. Lower panel: evolution of the mass transfer rate. The dotted lines represent the steady burning region.

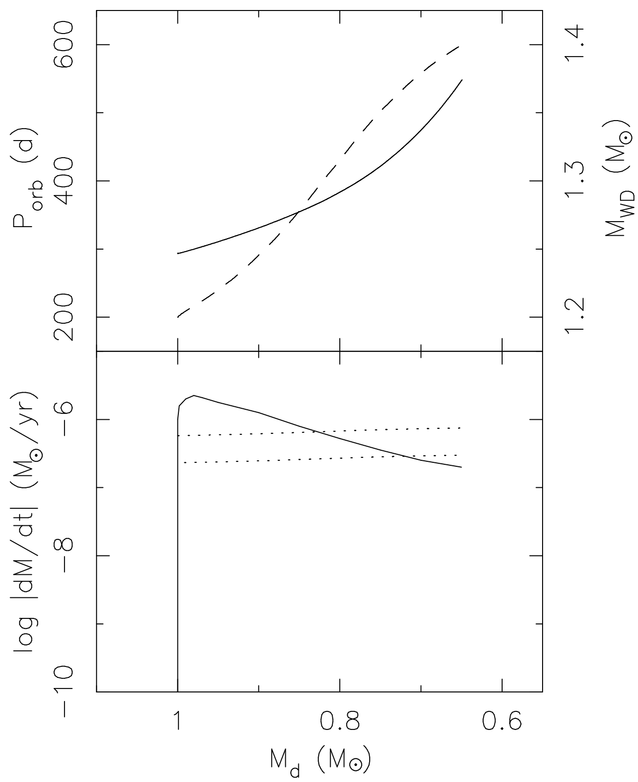

Fig. 2. Same as Fig. 1, but with $M_{\rm WD,0} = 1.2M_\odot$, $M_{\rm d,0} = 1.0M_\odot$ and $P_{\rm orb,0} = 300$ d.

mass transfer rate, as in Fig. 1, is high enough to maintain stable hydrogen burning and weak helium flashes to increase the white dwarf mass. The orbital period increases as mass is transferred from the less massive donor to the white dwarf. Similar features can also be found in Fig. 2 in Hachisu et al. (1996).

We summarize the final outcome of our evolutionary calculations in Fig. 3, showing the distribution of the progenitor systems of SNe Ia in the $M_{\rm d,0} - P_{\rm orb,0}$ diagram. For given white dwarf masses, Fig. 3 shows the lower and upper boundaries of the initial orbital period and the companion mass, within which the mass transfer is suitable for the white dwarf to grow to $1.4M_\odot$ (filled and open circles correspond to $M_{\rm WD,0} = 1.2$ and $1M_\odot$, respectively). It can be seen that there are two "islands", or two types of progenitor systems in the $M_{\rm d,0} - P_{\rm orb,0}$ diagram. One is close binaries that contain a massive ($M_{\rm d,0} \sim 2 - 3.5M_\odot$) donor with an initial orbital period of several tenth of a day to several days, and mass transfer occurring in Case A and Case B (see dotted curves in the figure). The initial white dwarf mass that may increase to $1.4M_\odot$ in this case can actually be as low as $0.9M_\odot$. The other is low-mass ($M_{\rm d,0} \sim 1M_\odot$) binaries with long orbital period (tens to hundreds of days), in which the donor is a red giant, i.e., in shell hydrogen burning phase, and the required initial mass of the white dwarf is $\sim 1.2M_\odot$, a bit larger than the value ($0.9M_\odot$) suggested by Hachisu et al. (1996). This is because Hachisu et al. (1996) assumed that all hydrogen is converted into helium, and then to heavier elements when the mass transfer rate becomes $\sim 10^{-7}M_\odot$ yr^{-1} after the wind stops. In our calculations we combined the results of Prialnik & Kovetz (1995) and Kato et al. (1989) for the accumulation ratio, and found it generally $\lesssim 0.3$, which makes it difficult for lower-mass white dwarfs to grow to $1.4M_\odot$. The results, however, are *not* conclusive due to the uncertainties in the accumulation ratio.

According to the standard model for SSS by van den Heuvel et al. (1992), one can see from Fig. 3 that not all SSS will evolve to SNe Ia: no SN Ia is produced when the initial donor mass lies between $\sim$ 1.3 and $\sim 2M_\odot$. The mass transfer rates in such cases either rise beyond $10^{-4}M_\odot$ yr^{-1} or rapidly decrease below $10^{-7}M_\odot$ yr^{-1} before $M_{\rm WD}$ reaches $1.4M_\odot$. On the other hand, the hot white dwarfs in the SN Ia progenitor systems may not be observed during the wind phase due to the self-absorption of X-rays by the wind itself, until the mass transfer rate decreases below $\dot{M}_{\rm up}$ and the wind stops (Hachisu et al. 1996). However, the observations of RX J0513.9-6951 suggest that if $\dot{M}$ is not much above $10^{-6}M_\odot$ yr^{-1}, the white dwarf can still be seen as a supersoft X-ray source.

Using the method suggested by Iben & Tutukov (1984), one can estimate the birth rate of SNe Ia, based on Fig. 3, to be $\sim 2 \times 10^{-3}$ yr^{-1} in our Galaxy, roughly consistent with the observed rate. The two types of progenitor systems in Fig. 3 can also qualitatively account for SN Ia explosions in both spiral and elliptical galaxies.

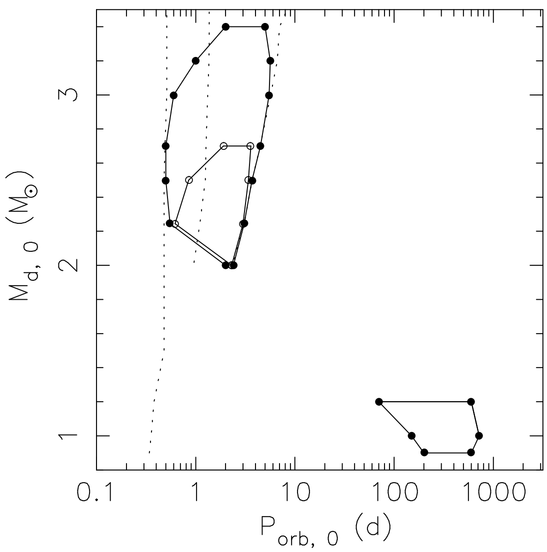

Fig. 3. Distribution of the progenitors of SNe Ia in the $M_{d,0} - P_{orb,0}$ diagram. The filled dots denote the boundary of the initial orbital period at the beginning of the mass transfer, for a white dwarf of $1.2M_\odot$ initial mass with a specific companion star, and circles for $1M_\odot$ white dwarfs. The dotted lines represent the boundary of mass transfer in Case A and Case B (from left to right).

We finally discuss the main uncertainties in our work. Firstly, only the Chandrasekhar-mass white dwarf model for SNe Ia is considered. Though it is more preferred by observations than the sub-Chandrasekhar-mass model, the latter can not be ruled out (cf. Branch et al. 1995). Secondly, the strong wind claimed by Hachisu et al (1996) is a breakthrough in the binary evolution theory. Its reliability, however, needs verification by more detailed theoretical calculations and observations. Thirdly, the accumulation ratio of the accreted matter is very difficult to estimate, due to the complicated situation on the surface of a white dwarf. It depends on the mass and temperature of the white dwarf, as well as the mass transfer rate. For hydrogen burning, Prialnik & Kovetz (1995) performed multi-dimensional calculations, but their results are still uncertain (MacDonald 1996). For helium burning, the only calculation of the accumulation ratio we can find in the literature is by Kato et al. (1989) for a $1.3M_\odot$ white dwarf with the *old* opacities. It is worthwhile in this respect to emphasize the importance of careful study of the condition under which accreting white dwarfs can accumulate hydrogen and helium, the condition for hydrogen and helium explosions, and the accumulation efficiency during the steady and unsteady burning cases.

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