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Binary population synthesis study of the supersoft X-ray phase of single degenerate type Ia supernova progenitors *

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Abstract In the single degenerate (SD) scenario for type Ia supernovae (SNe Ia), a mass-accreting white dwarf is expected to experience a supersoft X-ray source (SSS) phase. However, some recent observations showed that the expected number of mass-accreting WDs is much lower than that predicted from theory, regardless of whether they are in spiral or elliptical galaxies. In this paper, we performed a binary population synthesis study on the relative duration of the SSS phase to their whole mass-increasing phase of WDs leading to SNe Ia. We found that for about 40% of the progenitor systems, the relative duration is shorter than 2% and the evolution of the mean relative duration shows that it is always smaller than 5%, both for young and old SNe Ia. In addition, before the SNe Ia explosions, more than 55% of the progenitor systems were experiencing a dwarf novae phase and no more than 10% were staying in the SSS phase. These results are consistent with the recent observations and imply that both in early- and late-type galaxies, only a small fraction of mass-accreting WDs resulting in SNe Ia contributes to the supersoft X-ray flux. So, although our results are not directly related to the X-ray output of the SN Ia progenitor, the low supersoft X-ray luminosity observed in early type galaxies may not be able to exclude the validity of the SD model. On the contrary, it is evidence to support the SD scenario.

Key words: stars: white dwarfs — stars: supernovae: general

1 INTRODUCTION

Although Type Ia supernovae (SNe Ia) are very important in astrophysics, i.e. as standard candles to measure cosmological parameters (Riess et al. 1998; Perlmutter et al. 1999), the exact nature of their progenitors is still unclear (Hillebrandt & Niemeyer 2000; Leibundgut 2000; Parthasarathy et al. 2007). There is a consensus that SNe Ia result from the thermonuclear explosion of a carbon–oxygen white dwarf (CO WD) in a binary system (Hoyle & Fowler 1960). According to the nature of the companions of the mass accreting WDs, two basic scenarios for the progenitors of SNe Ia have been discussed over the last three decades. One is the single degenerate (SD) model (Whelan & Iben 1973; Nomoto et al. 1984), i.e. the companion is a main-sequence or a slightly evolved star (WD+MS), a red giant star (WD+RG) or a helium star (WD + He star) (Li & van den Heuvel

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1997; Hachisu et al. 1999; Langer et al. 2000; Han & Podsiadlowski 2004; Chen & Li 2007; Meng et al. 2009; Lü et al. 2009; Wang et al. 2009; Meng & Yang 2010b; Wang et al. 2010). The other is the double degenerate (DD) model, i.e. the companion is another CO WD (Iben & Tutukov 1984; Webbink 1984).

It is believed that the X-ray signature of these two possible scenarios is very different, i.e. no strong X-ray emission is expected from the DD scenario until shortly before the SN Ia explosion, but the mass-accreting WD may show the signatures of supersoft X-ray sources (SSSs) long before it explodes as an SN Ia. This provides a potential method for distinguishing between the SD and DD models. Recently, Gilfanov & Bogdán (2010) (hereafter GB10) obtained the 0.3–0.7 keV soft X-ray luminosity and the K-band luminosity of several early type galaxies. By comparing the detected X-ray luminosity with those predicted from the SN Ia rate estimated from the K-band luminosity, they found that the observed X-ray flux from the early type galaxies is a factor of $\sim 30 - 50$ less than predicted from the SD accretion scenario and then they concluded that no more than five percent of SNe Ia in early type galaxies can be produced by mass-accreting white dwarfs from the SD scenario. However, as noticed by Hachisu et al. (2010), the results of GB10 are based on an assumption that all the accreting WDs are in the SSS phase which lasts for about two million years before the SN Ia explosion. This assumption is rather simple and may overestimate the duration of the SSS phase by a factor of 10. Hachisu et al. (2010) recalculated their symbiotic model and found that the results in GB10 strongly support the SD scenario as a main contributor of SNe Ia in early type galaxies. Similar to GB10, Di Stefano (2010) also noticed that the predicted SSS number from the SD model in spiral galaxies is also much larger than that from observations, which may imply that the duration of the SSS phase from the SD scenario is much shorter than the accreting time of the WD, as presented in Hachisu et al. (2010). Actually, many works have referred to this problem, i.e. the duration of the SSS phase for an accreting WD is very short (see Yungelson et al. 1996; Han & Podsiadlowski 2004; Meng et al. 2009; Meng & Yang 2010a). In Meng & Yang (2010a), they calculated a dense model grid including WD + MS and WD + RG systems and the calculations obtained a very short duration of SSS phase for an accreting WD; the typical value is $1.5 - 4.5 \times 10^5$ years which is consistent with the calculation of Hachisu et al. (2010) (see figs. 1 and 2 in Meng & Yang 2010a). In this paper, we want to use the calculations in Meng & Yang (2010a) to do a binary population synthesis study to check whether or not the SD model in Meng & Yang (2010a) may explain the discoveries of Di Stefano (2010) and GB10.

In Section 2, we describe our method and we present the calculation results in Section 3. In Section 4, we show discussions and our main conclusions.

2 METHOD

Recently, Meng & Yang (2010a) constructed a comprehensive single degenerate progenitor model for SNe Ia. In the model, the mass-stripping effect of optically thick wind (Hachisu et al. 1996) and the effect of a thermally unstable disk were included (Hachisu et al. 2008; Xu & Li 2009). The prescription of Hachisu et al. (1999) on WDs accreting hydrogen-rich material from their companions was applied to calculate the WD mass growth. The optically thick wind and the material stripped-off by the wind were assumed to take away the specific angular momentum of the WD and its companion, respectively. In Meng & Yang (2010a), both the WD + MS channel and WD + RG channel are considered, i.e. Roche lobe overflow (RLOF) begins at the MS or RG stage. The Galactic birth rate of SNe Ia derived from that model is comparable with that from observations. In addition, that model may even explain some supernovae with low hydrogen mass in their explosion ejecta (Meng & Yang 2010c). In their calculations, the progenitor system may experience a wind (Case Wind), a calm hydrogen-burning (Case Calm), a nova explosion (Case Nova) or a dwarf nova phase (Case DNova). If a system is undergoing a calm hydrogen-burning phase, it may show the properties of SSSs. Meng & Yang (2010a) calculated more than 1600 WD close binary evolutions and showed the initial parameter space leading to SNe Ia is in an orbital period - secondary mass ($\log P_{\rm i}, M_2^{\rm i}$) plane. Their calculation is comprehensive and the evolutionary details of all the models are obtained but not sorted for publishing. In this paper, we extract the evolutionary properties of the models from the data files of the calculations and incorporate them into the BPS code developed by Hurley et al. (2000, 2002) to obtain the relative durations of the SSS phase, including the whole mass-increasing time of WDs leading to SNe Ia.

We summarize the assumptions for mass accretion in Meng & Yang (2010a). In an initial binary system, the companion fills its Roche lobe at MS or during HG or RG and mass transfer occurs. They assume that the transferred materials form a disk around the CO WD. If the mass-transfer rate is lower than a critical mass-transfer rate, the disk is thermally unstable and a dwarf nova is expected, otherwise the WD accretes the transferred material smoothly at a rate $\dot{M}_{\rm a} = |\dot{M}_{\rm tr}|$, where the critical mass-transfer rate is a function of the orbital period of the binary system

$$\dot{M}_{\rm c,th} = 4.3 \times 10^{-9} \left(\frac{P_{\rm orb}}{4{\rm hr}}\right)^{1.7} M_{\odot}\ {\rm yr}^{-1}, \tag{1}$$

where $P_{\rm orb}$ is the orbital period in hours (Osaki 1996; van Paradijs 1996). If the accretion rate of a CO WD, $\dot{M}_{\rm a}$, is larger than a critical value, an optically thick wind occurs (Hachisu et al. 1996), where the critical accretion rate is

$$\dot{M}_{\rm c,H} = 5.3 \times 10^{-7} \frac{(1.7 - X)}{X} (M_{\rm WD} - 0.4)\ M_{\odot}\ {\rm yr}^{-1}, \tag{2}$$

where X is the hydrogen mass fraction and $M_{\rm WD}$ is the mass of the accreting WD (mass is in $M_{\odot}$ and the mass-accretion rate is in $M_{\odot}\ {\rm yr}^{-1}$, Hachisu et al. 1999). If $\dot{M}_{\rm a}$ is smaller than $\dot{M}_{\rm c,H}$, but higher than $\frac{1}{2}\dot{M}_{\rm c,H}$, the hydrogen-shell burning is steady, i.e. the system is experiencing an SSS phase. When $\dot{M}_{\rm a}$ is lower than $\frac{1}{2}\dot{M}_{\rm c,H}$ but higher than $\frac{1}{8}\dot{M}_{\rm c,H}$, a very weak shell flash is triggered and then a recurrent nova is expected. When $\dot{M}_{\rm a}$ is lower than $\frac{1}{8}\dot{M}_{\rm c,H}$, the shell flash is so strong that no material is accumulated on the surface of the CO WD[1].

We extract the evolutionary time of Case Calm from all the binary system calculated in Meng & Yang (2010a) and found that the typical value for the SSS phase is $1.5 - 4.5 \times 10^5$ years which is consistent with the calculation of Hachisu et al. (2010). Since Hachisu et al. (2010) have discussed it, we will focus on the relative duration of the SSS phase to the whole mass-increasing time of a CO WD until the SN Ia explosion, $t_{\rm SSS}/t_{\rm SN}$, the fraction of the time spent in the SSS phase. Please keep in mind that as observational X-ray output of a nuclear-burning WD nonlinearly increases with its mass, i.e. it depends on the evolutional details of WD binary systems, the results obtained in this paper are not directly related to the X-ray output of the SN Ia progenitor. However, the results here may at least partly reveal the X-ray nature of the SN Ia progenitor.

To obtain the distribution of $t_{\rm SSS}/t_{\rm SN}$, we have performed a series of detailed Monte Carlo simulations via Hurley's rapid binary evolution code (Hurley et al. 2000, 2002). In the simulations, if a binary system evolves to a WD + MS or WD + RG stage and the system is located in the ($\log P^{\rm i}, M_2^{\rm i}$) plane for SNe Ia at the onset of RLOF, we assume that an SN Ia is produced. Then $t_{\rm SSS}/t_{\rm SN}$ is obtained by interpolation in the three-dimensional grid ($M_{\rm WD}^{\rm i}, M_2^{\rm i}, \log P^{\rm i}$) of the more than 1600 close WD binary systems calculated in Meng & Yang (2010a). In the simulations, we follow the evolution of 10^7 sample binaries. The evolutional channel is described in Meng & Yang (2010a). As in Meng & Yang (2010a), we adopted the following input for the simulations.

(1) A single starburst or a constant star formation rate is assumed.
(2) The initial mass function (IMF) of Miller & Scalo (1979) is adopted.
(3) The mass-ratio distribution is taken to be constant.

[1] Actually, the mass of the WD is reduced when a WD undergoes a nova explosion.

(4) The distribution of separations is taken to be constant in $\log a$ for wide binaries, where a is the orbital separation.
(5) A circular orbit is assumed for all binaries.
(6) The common envelope (CE) ejection efficiency $\alpha_{\rm CE}$, which denotes the fraction of the released orbital energy used to eject the CE, is set to 1.0 or 3.0 (see Meng & Yang 2010a for details).

3 RESULTS

3.1 Relative Duration of the SSS Phase

In Figure 1, we show the current-epoch-snapshot distribution of $t_{\rm SSS}/t_{\rm SN}$ for different $\alpha_{\rm CE}$, where a constant star formation rate is assumed. We can see from the figure that the distributions are similar to each other for different $\alpha_{\rm CE}$. A remarkable feature in the figure is that about 40% of mass-accreting CO WDs leading to SNe Ia spend less than 2% of their mass-increasing time in the SSS phase. Actually, for most of these WDs, the relative duration of the SSS phase is only about $10^{-3} - 10^{-4}$. No WD has a relative duration in the SSS phase accounting for more than 30%, which means that if we assume that the WDs show the signatures of SSSs during their whole mass-increasing time until SNe Ia, the number of SSSs is at least overestimated by a factor of three. In the distributions, there is a smaller bump between 0.16 and 0.2, which corresponds to the systems with an initial WD mass of $0.6 \sim 0.8\ M_{\odot}$, or a primordial primary of $2.5 \sim 3.5\ M_{\odot}$ (see fig. 2, Meng et al. 2008). In Figure 2, we give the distributions of the relative duration of the SSS phase and the initial WD mass for $\alpha_{\rm CE} = 1.0$ (The distributions of $\alpha_{\rm CE} = 3.0$ are similar to those of $\alpha_{\rm CE} = 1.0$). From the figure, we can see that whatever the initial WD mass is, the low relative duration of the SSS phase (less than 2%) is dominant.

To explore the contribution of the accreting WD to the soft X-ray flux of galaxies, a mean relative duration of the SSS phase is necessary. Since the relative duration of the SSS phase covers two orders of magnitude, we use a geometric mean to denote their mean value. Figure 3 shows the evolution of the mean relative duration of the SSS phase for a single star burst. It is amazing that the mean relative duration is always smaller than 5% from $\sim 10^8 - 10^{10}$ yrs, which may imply that even in spiral galaxies, only a small fraction of the mass-accreting WDs leading to SNe Ia contribute to supersoft X-ray flux.

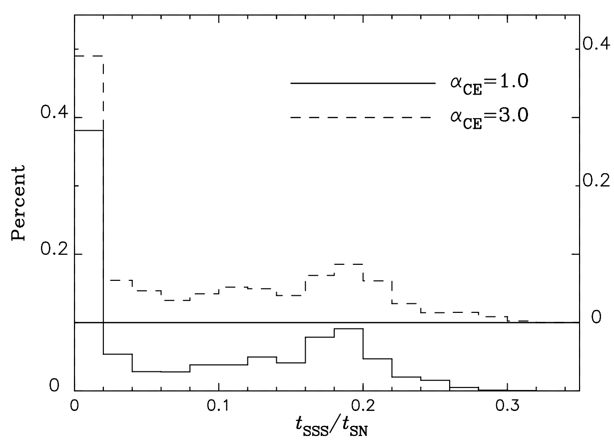

Fig. 1 Distribution of the relative duration of the SSS phase to the whole mass-increasing time of CO WDs until the SNe Ia explosion, $t_{\rm SSS}/t_{\rm SN}$, for a constant star formation rate with different $\alpha_{\rm CE}$ (*solid line*: $\alpha_{\rm CE} = 1.0$; *dashed line*: $\alpha_{\rm CE} = 3.0$). For $\alpha_{\rm CE} = 3.0$, the line is moved up by 0.1.

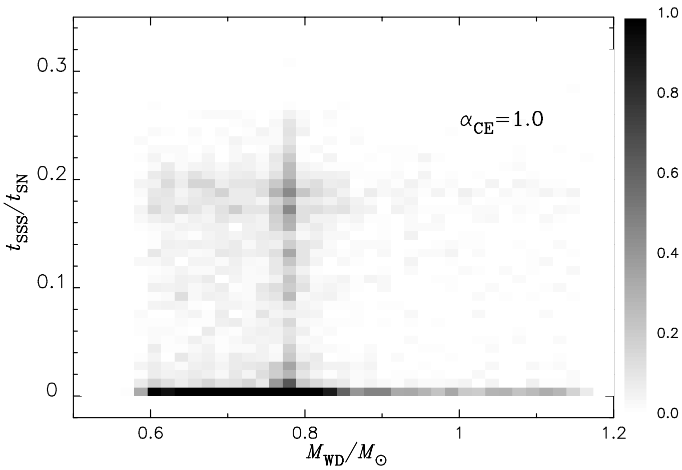

Fig. 2 Distribution of the relative duration of the SSS phase and initial WD mass with $\alpha_{\rm CE} = 1.0$.

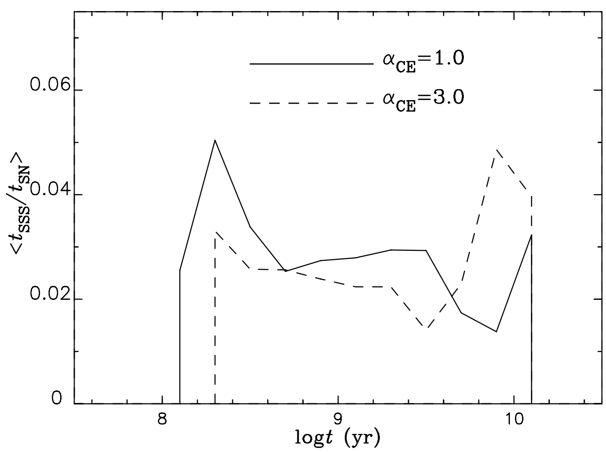

Fig. 3 Evolution of the mean relative duration of the SSS phase to the whole mass-increasing time of CO WD until the SN Ia explosion for a single starburst with different $\alpha_{\rm CE}$ (*solid line*: $\alpha_{\rm CE} = 1.0$; *dashed line*: $\alpha_{\rm CE} = 3.0$).

3.2 Class

In the calculations of Meng & Yang (2010a), the SNe Ia may explode at the wind, SSS, recurrent novae or go through the dwarf nova phase. In Figure 4, we show the relative importance of wind, SSS, nova and dwarf nova at the SN Ia explosion. We can see from the figure that more than 55% of the progenitor systems show the properties of dwarf novae before SNe Ia and about 30% are recurrent novae. Only no more than 10% of the progenitor systems experience the SSS phase. There are about 2% –10% (depending on $\alpha_{\rm CE}$) of the SNe Ia exploding in the wind phase. These SNe Ia may show the properties of 2006X-like SNe Ia (see Meng et al. 2010). Then, even before the SN Ia explosion, the SSS is still not a dominant state.

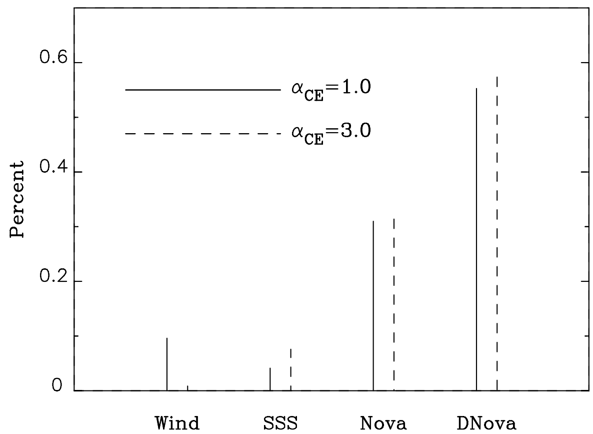

Fig. 4 Relative importance of wind, SSS, nova and dwarf nova at the SN Ia explosion for a constant star formation rate with different $\alpha_{\rm CE}$ (*solid line*: $\alpha_{\rm CE} = 1.0$; *dashed line*: $\alpha_{\rm CE} = 3.0$).

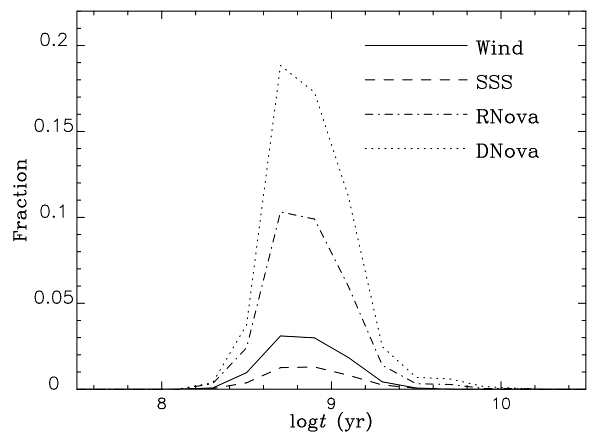

Fig. 5 Evolution of the fraction of wind, SSS, recurrent nova and dwarf nova at SN Ia explosion for a single starburst with $\alpha_{\rm CE} = 1.0$.

Figure 5 gives the evolution of the fraction of SNe Ia exploding at the wind, SSS, recurrent nova and dwarf nova phase for a single starburst. Here, we only present the case of $\alpha_{\rm CE} = 1.0$ since the case of $\alpha_{\rm CE} = 3.0$ is similar. As we can see from the figure, when age is longer than 2 Gyr, there are no SNe Ia exploding at the SSS phase and almost all SNe Ia are exploding at the dwarf nova phase. Considering that supersoft X-ray radiation from a dwarf nova is rare (see discussions in Hachisu et al. 2010), the discovery by GB10, that the supersoft X-ray flux is very low in early type galaxies, is a natural result.

4 DISCUSSION AND CONCLUSIONS

In this paper, we give the distribution of the relative duration of the SSS phase and the evolution of the distribution. Our results show that the duration of the SSS phase for accreting WDs is very short compared with their mass-increasing time. This result implies that if we assume that WDs radiate supersoft X-rays during their entire mass-increasing phase, the number of SSS cases should be overestimated significantly. The statement in GB10 that no more than 5% of SNe Ia in early type galaxies can be produced by mass-accreting white dwarfs in the SD scenario is just based on this simple assumption. Our BPS study shows that the mean relative duration of the SSS phase is always smaller than 5% for SNe Ia with both short- and long-delay times, which is consistent with the discoveries of GB10 and Di Stefano (2010). Our results mean that in spiral or elliptical galaxies, the fraction of mass-accreting WDs contributing to supersoft X-ray emission is very small, as suspected by Di Stefano (2010). So, the discoveries of GB10 and Di Stefano (2010) could be evidence to support the SD scenario for the SNe Ia progenitor model and then we cannot use the low supersoft X-ray luminosity of galaxies or the low number of mass-accreting WDs showing supersoft X-ray signal in elliptical galaxies to exclude the validity of the SD model.

In addition, please keep in mind that there is another uncertainty in GB10 in that they assume all the supersoft X-rays come from the mass accreting WDs which will finally explode as SNe Ia. Actually, the SSS cases at $t = 10^{10}$ yr are most likely not the progenitors of SNe Ia, no matter if in spiral or elliptical galaxies (Yungelson 2010). For example, some progenitor systems may experience an SSS phase, but the nova explosion prevents them from finally becoming SNe Ia (see the figs. 3 and 4 in Meng & Yang 2010a). Then, the contribution of mass-accreting WDs resulting in SNe Ia contributing to supersoft X-ray flux may be smaller than those shown in this paper, as discussed in Hachisu et al. (2010).

However, there are some uncertainties from our results in this paper. First, as is well known, a WD radius decreases as its mass increases. Correspondingly, at the same accretion rate $\dot{M}$ and luminosity, a less massive WD would have a lower temperature and then more soft X-rays (van den Heuvel et al. 1992). Calculation shows that WDs less massive than about $1\,M_{\odot}$ do not contribute to the statistics of SSSs (Di Stefano 2010). The soft X-ray emission from galaxies is dominated by the emission from the most massive WDs (maybe close to the Chandrasekhar mass limit because of the special X-ray band, i.e. 0.3–0.7 keV in Gilfanov & Bogdán 2010). For the reason above, the total luminosity of SN Ia progenitors not only simply scales with the duration of the super-soft phase but also depends on the details of their evolutional tracks. Since most of the SSSs happen when WD masses are around $1.2 - 1.3\,M_{\odot}$ (see Meng & Yang 2010a), it should be taken as an upper limit of the real cases for the number of SSSs deduced from the results in this paper. Then, this uncertainty cannot change our basic conclusion, i.e. GB10 overestimate the number of SSSs.

Secondarily, a part of accreting ONeMg WDs may also contribute to the soft X-rays and their contribution was not considered here, which may make us underestimate the number of SSSs. Fortunately, the number of ONeMg WDs must be much smaller than that of the CO WDs considered here because of the initial mass function. So, the basic conclusions in this paper still hold.

Thirdly, in this paper, we consider a new possible mechanism for SNe Ia, i.e. a dwarf nova, which is from a disk instability (Osaki 1996; van Paradijs 1996). For a low amount of accreted material during an outburst, the accreted matter may simply accumulate onto the WD but remains unburnt. After a few tens of disk instabilities, the accreted material finally reaches a critical mass which may result in a shell flash. This could be nothing else but a classical (or recurrent) nova (see also Hachisu et al. 2010). This scenario was upheld by observations (Wils et al. 2010). However, its SSS duration is too short to be compared with the steady SSS duration (Hachisu et al. 2010). Then, our result, that the dwarf nova is the dominant progenitor for old SNe Ia, may imply that the total luminosity of SSSs in early type galaxies would be much smaller than that predicted by GB10, which is consistent with the observation of GB10. In addition, Gilfanov & Bogdan (2011) recently argued that a WD with unstable nuclear burning, the classical/recurrent nova, may not be the main class of SN Ia progenitors in early type galaxies because they would be producing too many recurrent nova outbursts, which is inconsistent with classical nova statistics in nearby galaxies; the observational rate of classical novae with decay times shorter than 20 days is overestimated by a factor of 45–75.

This inconsistency seems to be more evidence against the validity of the SD scenario in early type galaxies. Actually, in this paper, the dwarf nova is the dominant one for the progenitor of SNe Ia in early type galaxies based on the calculation of Meng & Yang (2010a). In Meng & Yang (2010a), the duty cycle for dwarf novae is set to be 0.01 (typical range is from 0.1 to a few 10^{-3}), which means that if the dwarf nova is a possible channel for SNe Ia in early type galaxies, the estimated rate of classical novae in Gilfanov & Bogdan (2011) could be overestimated by a factor of 100 (typical range is from 10 to several 10^2). Considering that there are still some recurrent novae contributing to SNe Ia in early type galaxies, the overestimated factor of 45-75 by Gilfanov & Bogdan (2011) could be a natural result and should also not be a key argument against the SD channel in early type galaxies.

Finally, some mass-accreting WDs may not explode as SNe Ia and the contribution of these WDs to soft X-ray luminosity was not considered in this paper. However, the parameter space for these WDs is much smaller than those exploding as SNe Ia (Meng & Yang 2010a). Furthermore, the relative duration of the SSS phase for these WDs is much smaller than those exploding as SNe Ia. So, the missing WDs may not significantly affect our discussions in this paper.

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