SUPERSOFT X-RAY PHASE OF SINGLE DEGENERATE TYPE Ia SUPERNOVA PROGENITORS IN EARLY-TYPE GALAXIES

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Received 2010 March 7; accepted 2010 October 26; published 2010 November 11

ABSTRACT

In the single degenerate (SD) scenario for Type Ia supernova (SN Ia) progenitors, an accreting white dwarf (WD) is expected to undergo a supersoft X-ray source (SSS) phase. Recently, Gilfanov & Bogdán (hereafter GB10) claimed that observed X-ray fluxes of early-type galaxies would be too low to be consistent with the prediction of the SD scenario based on rather simple assumptions. We present realistic evolutionary models of SD systems and calculate durations of SSS phases. In most cases, accreting WDs spend a large fraction of time in the optically thick wind phase and the recurrent nova phase rather than the SSS phase. Thus, the SSS phase lasts only for a few hundred thousand years. This is by a factor of \(\sim 10\) shorter than those adopted by GB10 where the SN Ia progenitor WD was assumed to spend most of its life as an SSS. The theoretical X-ray luminosity of the SSS has a large uncertainty because of the uncertain atmospheric model of mass-accreting WDs and absorption of soft X-rays by the companion star’s cool wind material. We thus adopt an average of the observed fluxes of existing symbiotic SSSs, i.e., \(\sim 0.4 \times 10^{36} \text{ erg s}^{-1}\) for 0.3–0.7 keV. Using these SSS duration and soft X-ray luminosity, we show that the observed X-ray flux obtained by GB10 is rather consistent with our estimated flux in early-type galaxies based on the SD scenario. This provides strong support for the SD scenario as a main contributor of SNe Ia in early-type galaxies.

Key words: binaries: close – galaxies: evolution – stars: winds, outflows – supernovae: general – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) play very important roles in astrophysics as a standard candle to measure cosmological distances as well as the production site of a large part of iron group elements. However, the nature of SN Ia progenitors has not been clarified yet (e.g., Hillebrandt & Niemeyer 2000; Livio 2000; Nomoto et al. 1997, 2000). It has been commonly agreed that the exploding star is a carbon–oxygen (C+O) white dwarf (WD) and the observed features of SNe Ia are better explained by the Chandrasekhar mass model than the sub-Chandrasekhar mass model. However, there has been no clear observational indication as to how the WD mass gets close enough to the Chandrasekhar mass.

The X-ray signature of these two possible paths are very different. It is believed that no strong X-ray emission is expected from the merger scenario until shortly before the SN Ia explosion. On the other hand, the accreting WD becomes a supersoft X-ray source (SSS) long before the SN Ia explosion, for a million years. In order to constrain progenitor models in early-type galaxies, Gilfanov & Bogdán (2010, hereafter GB10) recently obtained the 0.3–0.7 keV soft X-ray luminosity \(L_{X,\text{obs}}\) and the \(K\)-band luminosity \(L_K\) for several early-type galaxies. They compared \(L_{X,\text{obs}}\) with those predicted from the SN Ia birth rate estimated from \(L_K\). Their predicted X-ray luminosity \(L_{X,\text{SSS}}\) from the SD scenario is 40–70 times larger than \(L_{X,\text{obs}}\) and they concluded that no more than \(5\%\) of SNe Ia in early-type galaxies can be produced by mass-accreting WDs of the SD scenario. However, their \(L_{X,\text{SSS}}\) is based on the following assumptions, which involves large uncertainties. They assumed that (1) all the accreting WDs are in the SSS phase which typically lasts for two million years before an SN Ia explosion and (2) the observed (including absorption) 0.3–0.7 keV soft X-ray flux is as large as \((3–5) \times 10^{36} \text{ erg s}^{-1}\) per source.

In a canonical SD scenario (e.g., Hachisu et al. 1999a), however, the accreting WDs usually spend a large fraction of the lifetime in the optically thick wind phase and in the recurrent nova (RN) phase, so that a duration of the SSS phase is much shorter than that assumed by GB10. Moreover, the X-ray luminosity of the symbiotic SSS has a large uncertainty because of the uncertain atmospheric model of mass-accreting WDs and absorption of soft X-rays by the companion star’s cool wind material. In these situations, it is reasonable that we use observed fluxes of existing symbiotic SSSs.

In this Letter, we show that the soft X-ray fluxes observed in early-type galaxies are consistent with those expected from the SD model, if we adopt a realistic scenario of binary evolutions including a shorter SSS duration and a much more absorbed soft X-ray flux estimated from existing symbiotic SSSs. We first show the short SSS duration of our SD models in Section 2. In Section 3, we estimate absorbed soft X-ray fluxes in early-type galaxies. Discussion follows in Section 4.

2. DURATION OF SUPERSOFT X-RAY SOURCE PHASE

In early-type galaxies, star formation virtually stopped several Gyr ago. Therefore, only the white dwarf (WD) + red giant
(RG) binary systems with the initial RG companion mass of $M_{2,0} \lesssim 1.3 M_\odot$ (e.g., Hachisu et al. 1999a) contribute to SNe Ia. For the white dwarf (WD) + main-sequence (MS) star binary systems, more massive companions (usually $M_{2,0} \gtrsim 1.8 M_\odot$; see, e.g., Hachisu et al. 1999b) are required but there remain no such massive ones because they have already evolved off. Therefore, here we estimate the duration of a supersoft X-ray phase only for the WD+RG systems.

Our evolutionary model for the SN Ia progenitor is as follows. The binary evolution starts from zero-age MS star pairs with a given set of the primary mass ($M_{1,i}$), secondary mass ($M_{2,i}$), and separation ($a_i$) as done in Hachisu et al. (1999a). Unless the initial separation of the binary components is too close, the more massive (primary) component evolves to an RG star (with a helium core) or an asymptotic giant branch star (with a C+O core) and fills its Roche lobe or blows a superwind. If subsequent mass transfer from the primary to the secondary is rapid enough to form a common envelope, the binary separation shrinks greatly owing to mass and angular momentum losses from the binary system during the common envelope evolution (see, e.g., Figure 1 of Hachisu et al. 1999a for an illustration of the binary evolution). The hydrogen-rich envelope of the primary component is stripped away and the primary becomes either a helium star or a C+O WD. The helium star further evolves to a C+O WD after a large part of helium is exhausted by core helium burning. Thus, we have a binary pair of the C+O WD and the secondary star that is still an MS. At this stage (denoted by 0), the binary becomes a pair of the C+O WD with the mass of $M_{WD,0}$ and the secondary star that is still on the MS; the mass of the secondary star, $M_{2,0}$, is still close to $M_{2,i}$, because the accreted mass during the common envelope phase is negligibly small.

After the secondary evolves to fill its Roche lobe, the WD accretes mass from the secondary and grows to the critical mass ($M_{IA} = 1.38 M_\odot$ in Nomoto 1982) to explode as an SN Ia if the initial binary orbital period ($P_0$) and the initial mass of the secondary ($M_{2,0}$) are in the regions (labeled “initial”) shown in Figure 1 of Hachisu et al. (2008). There are two separate regions: one is for binaries consisting of a WD and an MS (WD+MS) and the other is binaries consisting of a WD and an RG (WD+RG). In this figure, the metallicity and the initial mass of the WD were assumed to be $Z = 0.02$ and $M_{WD,0} = 1.0 M_\odot$. In early-type galaxies considered here, however, MS stars more massive than $1.3 M_\odot$ have already evolved off to RGs or WDs, so that only the WD+RG systems can produce SNe Ia.

After the mass transfer begins from the RG to the WD in our WD+RG systems, a steady-state SSS phase can be realized only when the mass accretion rate onto the WD satisfies

$$M_{st} < M_{WD} < M_{cr},$$

where $M_{st}$ is the lower limit mass accretion rate for stable hydrogen shell burning on the WD, $M_{WD}$ is the mass accretion rate onto the WD, and $M_{cr}$ is the critical mass accretion rate above which the WD envelope expands to blow optically thick winds (Hachisu et al. 1996, 1999a, 1999b). Nomoto et al. (2007) obtained these critical rates as

$$M_{st} = 3.066 \times 10^{-7} \left( \frac{M_{WD}}{M_\odot} - 0.5357 \right) M_\odot \text{ yr}^{-1},$$

and

$$M_{cr} = 6.682 \times 10^{-7} \left( \frac{M_{WD}}{M_\odot} - 0.4453 \right) M_\odot \text{ yr}^{-1}.$$
They assumed the number of accreting WDs in the SSS phase with the X-ray luminosity expected from the SN Ia birth rate. We obtained the duration of $P_{\text{SSS}} \sim 3.2 \times 10^5$ yr. We include the rate of mass stripping from the RG by the WD wind ($\dot{M}_{\text{wind}}$, that is, $-\dot{M}_{\text{wind}} \approx -\dot{M}_{\text{wind}} - \dot{M}_{\text{strip}}$ during the wind phase) and the mass loss during helium shell flashes ($\dot{M}_{\text{WD}} = \eta_{\text{HR}}(\dot{M}_{\text{RG}} - \dot{M}_{\text{strip}})$). See Equations (22) and (15) of Hachisu et al. (1999a), respectively. The WD and RG masses (solid lines) refer to the left axis while the mass loss/growth rates (dashed lines) refers to the right axis.

(A color version of this figure is available in the online journal.)

Figure 2. Time evolution of an SN Ia progenitor system for an initial set of parameters of $M_{\text{WD},0} = 0.9 M_\odot$, $M_{\text{L},0} = 1.3 M_\odot$, and $a_0 = 297 R_\odot$ ($P_0 = 400$ days). The WD blows optically thick winds until $t = P_{\text{wind}} \sim 7 \times 10^5$ yr, enters the SSS phase until $\sim 10.5 \times 10^5$ yr, then becomes an recurrent nova, and finally explodes as an SN Ia at $t_{\text{SN}} \sim 15.5 \times 10^5$ yr. We obtain the duration of $P_{\text{SSS}} \sim 3.2 \times 10^5$ yr. The wind mass-loss rate is $\dot{M}_{\text{WD}} \approx M_{\text{WD}} \sim M_{\text{WD}}$, Steady hydrogen shell burning with no optically thick winds occurs between $M_{\text{SN}} < M_{\text{WD}} \leq M_{\text{cr}}$. There is no steady state burning below $M_{\text{WD}} < M_{\text{SN}}$. Instead, intermittent shell flashes occur. The envelope mass, $M_{\text{env}}$, at which a hydrogen shell flash ignites, is also shown (taken from Figure 9 of Nomoto 1982). Progenitor’s crossing time of the region between $M_{\text{SN}} < M_{\text{WD}} \leq M_{\text{cr}}$, i.e., the duration of an SSS phase, is relatively short.

(A color version of this figure is available in the online journal.)

3. SOFT X-RAY FLUX IN THE SD MODEL

GB10 obtained the 0.3–0.7 keV soft X-ray to K-band luminosity ratio for several early-type galaxies and compared them with the X-ray luminosity expected from the SN Ia birth rate. They assumed the number of accreting WDs in the SSS phase as

$$N_{\text{WD,SSS}} \approx \frac{\Delta M_{\text{WD}}}{M_{\text{WD}}} N_{\text{SN}} \approx P_{\text{SSS}} N_{\text{SSS}},$$

where $\Delta M_{\text{WD}}$ is the mass difference between the initial mass ($M_{\text{WD},0}$) and the final mass ($M_{\text{f}}$), and $N_{\text{SN}}$ is the SN Ia birth rate given by

$$N_{\text{SN}} = \frac{1}{2} \times 3.5 \times 10^{-4} \left( \frac{L_K}{10^{10} L_K, \odot} \right) \text{yr}^{-1}. \quad (7)$$

If we adopt our real duration of $P_{\text{SSS}} \sim 2.5 \times 10^5$ yr, the number of WDs in the SSS phase is

$$N_{\text{WD,SSS}} \approx 44 \left( \frac{L_K}{10^{10} L_K, \odot} \right). \quad (8)$$

as tabulated in Table 1 together with the results of GB10. Since our real duration of $P_{\text{SSS}}$ is much shorter than those assumed by GB10, the number of accreting WDs is by a factor of $\sim 8$ smaller than those obtained by GB10.

We also point out that the soft X-ray flux from mass-accreting WDs in the SSS phase involves quite a large uncertainty. The key point is that the progenitor system is the WD+RG system, in which the WD is embedded in a complex circumbinary matter. Furthermore, we have not yet fully understood atmospheric structures of mass-accreting WDs in symbiotic stars (e.g., Jordan et al. 1996; Orio et al. 2007). In these situations, it is reasonable that we use observed fluxes of symbiotic SSSs with known distance like the member of the Small Magellanic Cloud (SMC). There are two well-studied symbiotic SSSs in the SMC, SMC 3 and Lin 358.

The soft X-ray flux (0.15–2.4 keV) from SMC 3 with ROSAT was obtained to be $\sim 3.3 \times 10^{36} (d/65 $kpc$)^2 \text{erg s}^{-1}$ by Kahabka et al. (1994). The flux between 0.3 and 0.7 keV is 0.3 and 0.4 of the total flux (see, e.g., Figures 2–6 of Jordan et al. 1996, for the spectrum), so that $f_X, \text{obs} \sim 1 \times 10^{36} \text{erg s}^{-1}$ for 0.3–0.7 keV. This Kahabka et al.’s flux has already been corrected for the Galactic absorption, i.e., $N_H = 3 \times 10^{20} \text{cm}^{-2}$ with an unknown factor, which is not specified in Kahabka et al. (1994). Thus, the absorbed flux at the Earth is smaller than $1 \times 10^{36} \text{erg s}^{-1}$. The 0.2–1.0 keV flux from SMC 3 outside eclipse was also

Figure 3. Evolutionary path (red solid) of an SN Ia progenitor (same model as in Figure 2) on the map of response of white dwarfs to mass accretion rate. The progenitor explodes at the star mark as an SN Ia. Strong optically thick winds blow above the line of $M_{\text{WD}} > M_{\text{cr}}$. The wind mass-loss rate is $\dot{M}_{\text{wind}} \approx M_{\text{WD}} - M_{\text{cr}}$. Steady hydrogen shell burning with no optically thick winds occurs between $M_{\text{SN}} < M_{\text{WD}} < M_{\text{cr}}$. There is no steady state burning below $M_{\text{WD}} < M_{\text{SN}}$. Instead, intermittent shell flashes occur. The envelope mass, $M_{\text{env}}$, at which a hydrogen shell flash ignites, is also shown (from Figure 9 of Nomoto 1982). Progenitor’s crossing time of the region between $M_{\text{SN}} < M_{\text{WD}} < M_{\text{cr}}$, i.e., the duration of an SSS phase, is relatively short.

(A color version of this figure is available in the online journal.)
observed with XMM-Newton, and Orio et al. (2007) obtained
\(\sim 3 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}\) at the Earth (M. Orio 2010, private
communication). The 0.3–0.7 keV flux is about 60% of the total
flux (see Figure 2 of Orio et al. 2007 for the spectrum),
i.e. \(f_{X, \text{obs}} = 1.8 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}\). We obtain \(\ell_{X, \text{obs}} = 4\pi d^2 f_{X, \text{obs}} = 7.7 \times 10^{33} \text{ erg cm}^{-2}\).

In this way, we have obtained expected absorbed flux from NGC3585 to be
\(\ell_{X, \text{cal}} = 6.8 \times 10^{33} \text{ erg cm}^{-2}\). In this way, we have obtained expected absorbed flux for each early-type galaxy listed in Table 1.

Another example is Lin 358, the SMC symbiotic star. The
absorbed soft X-ray flux (0.13–1.0 keV) from Lin 358 with XMM
Newton was estimated to be \(\sim 8.3 \times 10^{35} \text{d}/(60 \text{kpc})^2 \text{ erg cm}^{-2}\) with \(N_{H} = 7.6 \times 10^{20} \text{ cm}^{-2}\) and \(T = 2.3 \times 10^{5} \text{ K}\) by Kahabka & Haberl (2006). Since the spectrum is very soft,
the flux between 0.3 and 0.7 keV is at most 0.2 of the total flux
(see Figure 3 of Orio et al. 2007 for the spectrum). We obtain \(\ell_{X, \text{cal}} = 1.7 \times 10^{34} \text{ erg cm}^{-2}\) for 0.3–0.7 keV. The converted factor to
NGC3585 is 1.6 and we obtain the expected X-ray flux to be
\(\ell_{X, \text{cal}} = 2.7 \times 10^{34} \text{ erg cm}^{-2}\).

These two symbiotic stars have very different values of X-ray
flux, so we adopt an arithmetic mean of these two and each
\(\ell_{X, \text{cal}}\) is shown in Table 1. Then the total expected supersoft X-ray luminosity of \(L_{X, \text{SSS}}\) is obtained as
\[L_{X, \text{SSS}} = N_{\text{WD,SSS}} \times \ell_{X, \text{cal}},\]  
(9)
for the expected soft (0.3–0.7 keV) X-ray flux, that is also shown
in Table 1. The estimated soft X-ray fluxes are rather consistent with the observed ones of early-type galaxies. This is in apparent contradiction with the claim made by GB10.

4. DISCUSSION

Our estimated duration of \(P_{\text{SSS}} \sim 2.5^{+0.3}_{-0.3} \times 10^{5}\) yr is rather
stiff as long as our SD model is concerned. However, there is
still a large uncertainty on the absorbed soft X-ray flux. The
bright symbiotic SSSs are rather rare as Vogel & Morgan (1994,
p. 847) wrote “Its (SMC 3) X-ray luminosity in the 0.1–2.4 keV
energy band was estimated to be \(\sim 400 L_{\odot}\). This is an unusually
high X-ray flux for a symbiotic binary.” If SMC 3 is a brightest
exception considering low X-ray fluxes of other symbiotic SSSs
like Lin 358, our flux estimate in Table 1 may be reduced further.

As one of new possible mechanisms to SNe Ia, which might be
additional soft X-ray fluxes, King et al. (2003) speculated that
a dwarf nova could become an SSS during the outburst if \(M_{\text{WD}}\)
temporarily increases by a factor of \(10–100\) (i.e., \(M_{\text{WD}} > M_{\text{bh}}\)).
Such an SSS, however, cannot be realized. Hydrogen shell
burning does not occur in such a case because the accreted
envelope mass is too small to be ignited. For example, Starrfield
et al. (1998) calculated mass accretion onto the very massive WD
of \(1.35 M_{\odot}\). With a high accretion rate of \(1.1 \times 10^{-6} M_{\odot} \text{ yr}^{-1}\),
they found that hydrogen ignites 2.6 yr after the accretion starts.
This means that the accreted mass of \(3 \times 10^{-6} M_{\odot}\) should be
required before the hydrogen ignition.

In King et al.’s (2003) idea (see their Figure 2), the average
mass accretion rate is \(1 \times 10^{-9} M_{\odot} \text{ yr}^{-1}\) and the duty
cycle is 0.004, which means a burst mass accretion rate of
\(2.5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}\) (\(> M_{\odot}\)). The viscous timescale of
the accretion disk in the WD+RG systems like RS Oph is about a few to several hundred days or so (e.g., King &
Pringle 2009). Therefore, the disk mass can be estimated to be
\(2.5 \times 10^{-7} M_{\odot} \text{ yr}^{-1} \times (0.7–1.5) \text{ yr} = (2.4) \times 10^{-7} M_{\odot}\),
which is too small to trigger a shell burning even on a very massive WD
like in RS Oph. Even if a disk instability occurs, the accreted
matter simply accumulates on the WD but remains unburnt. Af-
fter a few tens of disk instabilities, the accreted material finally
reaches the critical mass of \(3 \times 10^{-6} M_{\odot}\) and results in a shell
flash. This is nothing else a classical (or recurrent) nova and its
SSS duration is too short to be compared with the steady SSS
duration as mentioned earlier.

We thank Joanna Mikołajewska for useful discussion on
symbiotic SSSs like SMC 3. We are also grateful to the
anonymous referees for their detailed comments that helped
improve the Letter. This research has been supported by the
Grant-in-Aid for Scientific Research of the Japan Society for
the Promotion of Science (20540226, 20540227) and by World
Premier International Research Center Initiative, MEXT, Japan.

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Table 1

| Galaxy   | \(L_{X}^{\text{obs}}\) \((10^{38} L_{\odot})\) | \(N_{\text{WD,SSS}}\) | \(\ell_{X, \text{cal}}\) \((10^{35} \text{ erg cm}^{-2} \text{s}^{-1})\) | \(L_{X, \text{obs}}\) \((10^{37} \text{ erg cm}^{-2} \text{s}^{-1})\) | \(L_{X, \text{SSS}}\) \((10^{37} \text{ erg cm}^{-2} \text{s}^{-1})\) |
|----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| M32      | 0.085           | 25              | 3.7             | 3.1             | 0.15            | 0.12            |
| NGC 3377 | 2.0             | 580             | 88              | 5.8             | 4.7             | 5.1             |
| M31 bulge| 3.7             | 1100            | 160             | 2.9             | 6.3             | 4.7             |
| M105     | 4.1             | 1200            | 180             | 5.9             | 8.3             | 11              |
| NGC 4278 | 5.5             | 1600            | 240             | 7.2             | 15              | 17              |
| NGC 3585 | 15              | 4400            | 660             | 3.5             | 38              | 23              |

Notes.

a Table 1 of GB10.
b This work, Equation (8).
c This work.
d This work, Equation (9).
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