Binary Paths to Type Ia Supernovae Explosions
Proceedings IAU Symposium No. 281, 2011
R. Di Stefano, M. Orio, & M. Moe, eds.

doi:10.1017/S1743921312014895

Why are Supersoft X-ray Fluxes So Weak in Early-type Galaxies? – A Clue to Type Ia SNe Progenitors –

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Abstract. Supersoft X-ray fluxes in early-type galaxies provide an excellent test for Type Ia supernovae (SNe Ia) progenitors: the double degenerate (DD) scenario is believed to produce no supersoft sources (SSSs) except just before the SN Ia explosion, while the single degenerate (SD) scenario produces SSSs in some phases of the symbiotic channel. Recent observations of the supersoft X-ray flux of early-type galaxies show a remarkable agreement with theoretical predictions of the SD scenario, which thus turns out to be a strong support for the SD scenario, despite the original observations aimed at the opposite conclusion. Here I explain why X-ray fluxes are so weak in early-type galaxies. (1) Candidate binaries in the SD scenario become SSSs only during a short time on their way to SNe Ia explosions, because they spend a large part of their lifetime in a wind phase. (2) During the SSS phase, symbiotic stars emit very weak supersoft X-ray fluxes even if the WD is very massive. It should be emphasized that supersoft X-ray symbiotic stars are very rare and we need more observations to understand their nature.

Keywords. binaries: symbiotic — stars: novae, cataclysmic variables, late-type, mass loss, white dwarfs, supernovae — X-rays: galaxies, stars

1. Supersoft X-ray Sources as Progenitors of SNe Ia in Early-type Galaxies

Type Ia supernovae (SNe Ia) play very important roles in astrophysics as standard candles to measure cosmological distances, as well as being production sites for a large part of iron group elements. However, the nature of SNe Ia progenitors has not been clarified yet. 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 for carbon ignition ($M_{\rm Ia} = 1.38\ M_\odot$), i.e., whether the WD accretes H/He-rich matter from its binary companion [single degenerate (SD) scenario] or two C+O WDs merge [double degenerate (DD) scenario].

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. In order to constrain progenitor models in early-type galaxies, Gilfanov & Bogdán (2010)(hereafter, GB10) obtained supersoft X-ray luminosity $L_{\rm X,obs}$ for several early-type galaxies as shown in the 7th column of Table 1. They concluded that these fluxes are much smaller than those expected from the SD scenario, and thus the SD scenario is not the major path to SNe Ia. On the other hand, Hachisu *et al.* (2010) (hereafter, HKN10) argued, based on the same data of GB10, that the

Table 1. Supersoft X-ray flux in early-type galaxies (0.3-0.7 keV).

Galaxy	$N_{\rm WD,SSS}$ GB10[b]	$N_{\rm WD,SSS}$ HKN10[b]	$l_{\rm X}^{a}$ 10^{35} erg s^{-1} GB10	$l_{\rm X}^{a}$ 10^{35} erg s^{-1} HKN10	$L_{\rm X,SSS}$ 10^{37} erg s^{-1} GB10	$L_{\rm X,obs}$ 10^{37} erg s^{-1} GB10	$L_{\rm X,SSS}$ 10^{37} erg s^{-1} HKN10
M32	25	3.7	28	3.1	7.1	0.15	0.12
NGC3377	580	88	47	5.8	270	4.7	5.1
M31 Bulge	1100	160	21	2.9	230	6.3	4.7
M105	1200	180	46	5.9	550	8.3	11
NGC4278	1600	240	48	7.2	760	15	17
NGC3585	4400	660	31	3.5	1400	38	23

Notes:
[a] mean supersoft X-ray flux per source
[b] GB10 refers to Gilfanov & Bogdán (2010), and HKN10 refers to Hachisu *et al.* (2010)

observed X-ray luminosities are very consistent with the SD scenario and thus, it is a strong observational support for the SD scenario. In this short report I will address what causes the difference between the two estimates by GB10 and HKN10 as well as current problems that must be studied in the future.

2. Supersoft X-ray Phase in Binary Evolution of the SD Scenario

The most important difference between GB10 and HKN10 is the number of WDs in the SSS phase. GB10 derived the expected SNe Ia rate for each galaxy, based on the K-band luminosity and the assumed SNe Ia rate per K-band luminosity. Then, GB10 derived the number of accreting WDs, $N_{\rm WD,SSS}$, assuming that all the WDs always stay in the SSS phase before the SN Ia explosion (e.g., it takes 2×10^6 yrs for a 1.2 $M_\odot$ WD to increase its mass to the Chandrasekhar mass with accretion rate of 1 $\times 10^{-7}$ $M_\odot$ yr^{-1}).

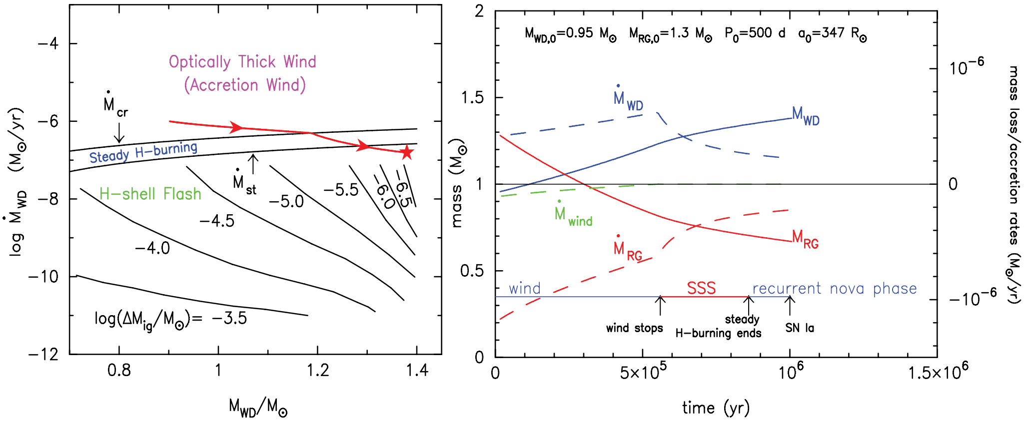

Figure 1. (left) A typical evolutionary path (*red solid*) of an SN Ia progenitor (in the SD scenario) on the map of response of WDs to mass accretion rate. Starting from the accretion wind phase, in which strong optically thick winds blow from the WD, the binary enters the supersoft X-ray phase, which is a narrow region between the accretion rate $\dot M_{\rm cr} > \dot M_{\rm WD} > \dot M_{\rm st}$. When the mass accretion rate decreases to less than the value to keep steady hydrogen-burning ($\dot M_{\rm st}$), the binary enters the recurrent nova (very weak shell flash) phase. The WD explodes at the star mark as an SN Ia. This figure is taken from Hachisu *et al.* (2010). (right) Evolution of a WD + RG system toward the Chandrasekhar mass limit. The mass transfer rate $\dot M_{\rm RG}$ from the RG in an early phase exceeds $\dot M_{\rm cr}$. Thus, the WD blows optically thick winds until $t = P_{\rm wind} \sim 5.5\times10^5$ yr and then enters a SSS phase. As the mass accretion rate decreases, it enters a recurrent nova phase and reaches the Chandrasekhar mass limit at $\sim 10^6$ yr.

This assumption, that a WD is always in the SSS phase, is however, very unlikely. In a canonical SD scenario (e.g. Hachisu *et al.* 1999), accreting WDs usually spend a large fraction of the lifetime in the optically thick wind phase, then undergo the SSS phase, and finally enter the recurrent novae (RNe) phase. Figure 1 (left) shows a typical evolutionary path of a mass-accreting WD by the arrows, and Figure 1 (right) demonstrates that the SSS phase is a relatively short fraction of the total lifetime. In binary evolution calculations, the secondary star decreases its mass because of mass transfer, and then the mass transfer rate to the WD naturally decreases with time. Therefore, the WD evolves from the SSS phase to an RNe phase as the WD mass increases. GB10 assumed that WDs always evolve along the narrow strip of 'steady H-burning' (i.e., the mass accretion rate increases with time), but this is very artificial and highly unlikely.

HKN10 followed the evolution of a number of binaries with different binary parameters and found that the SSS phase is as short as $P_{\rm SSS} \sim 2.5^{+0.9}_{-1.8} \times 10^5$ yr. Using this value HKN10 recalculated $N_{\rm WD,SSS}$ with the same K-band luminosity and SN rate as GB10, which is shown in the third column of Table 1. Comparing with GB10's estimates in the 2nd column, the number is reduced by a factor of 8.

3. Symbiotic Stars are Very Dark Supersoft X-ray Sources

A second discrepancy between GB10 and HKN10 is the "typical supersoft X-ray flux" of candidate symbiotic stars. GB10 assumed the absorbed X-ray flux $l_{\rm X}$ to be 2-5 $\times 10^{36}$ erg s^{-1} per source as in the 4th column of Table 1. These values are consistent with theoretical estimates if (1) the WD luminosity is $L \sim 10^{38}$ erg s^{-1}, (2) the surface temperature is $T_{\rm eff} = 45$ eV, (3) the energy band is 0.3-0.7 keV, and (4) there is no absorption except Galactic extinction (i.e., no intrinsic absorption of symbiotic stars and no absorption within the host early-type galaxies). On the other hand, HKN10 adopted observation-based values, 3-7 $\times 10^{35}$ erg s^{-1} as listed in the 5th column of Table 1; these small values are derived from arithmetic mean of absorbed fluxes of SMC3 and Lin358 with corrected absorptions.

Symbiotic stars are rarely supersoft X-ray sources (e.g. Mürset *et al.* 1997). There are no strong supersoft X-ray symbiotic stars in the Galaxy and LMC except in metal-poor environments. All the LMC steady H-burning WDs are close binaries. In the SMC, two supersoft X-ray symbiotic stars are known: SMC3 and Lin358. SMC3 is an exceptionally bright SSS among the symbiotics in our Galaxy/the local group (Mürset *et al.* 1997), whereas Lin358 is a weak SSS. As SMC stars are metal poor, these observational facts suggest a possibility that symbiotics become bright SSS only if metal-poor (J. Mikołajewska 2011: private communication at the conference). If this is the case, one cannot expect a larger number of bright SSS symbiotics in early-type galaxies that are not metal poor. Even if not, it is very unlikely that all the galaxies in Table 1 host a large number of symbiotic stars much brighter than the extraordinarily bright X-ray symbiotic star, SMC3.

Table 1 also shows the predicted supersoft X-ray fluxes for each galaxy, $L_{\rm X,SSS}$, which are obtained from the X-ray flux per source ($l_{\rm X}$) multiplied by the number of sources ($N_{\rm WD,SSS}$). Estimates by GB10 (6th column of Table 1) are 40-70 times larger than those by HKN10 (the last column). We see the values by HKN10 are quite consistent with the observational value, $L_{\rm X,obs}$, in the 7th column.

It should be stressed that we don't know much about symbiotic stars with steady burning, massive WDs, except the fact of no stronger SSS symbiotics than SMC3 in nearby galaxies. Then a question arises; why are symbiotic stars so dark in supersoft X-rays? In other words, what was inappropriate among the conditions (1)-(4) listed above?

One possibility is (4) absorption. Symbiotic binaries could have high intrinsic absorption (Sturm *et al.* 2011). Another possibility is (2) temperature. For a low surface temperature, the expected X-ray flux in a given energy band is sensitively reduced due to low transparency. In symbiotic binaries, a WD accretes matter from the red giant companion possibly in wind-fed accretion rather than in disk-accretion. With a high mass-accretion rate, the WD atmosphere may be swollen up due to gravitational energy release and could have a much lower temperature than in steady burning WDs with disk-fed-accretion (like LMC SSSs). In fact the WD temperature of the two SMC symbiotics are in the lower side of temperature distribution of LMC SSSs (20-80 eV): ~ 40 eV (Orio *et al.* 2007) and ~ 33 eV (Sturm *et al.* 2011) for SMC3, 19.6 eV for Lin358 (Kahabka & Haberl 2006). If the envelope is further swollen up, the temperature becomes too low to emit X-rays. Therefore, the temperature of 45 eV (GB10's suggestion) seems to be an upper limit and a much higher temperature is unlikely in symbiotic stars. However, note that we have only two samples and need more statistics/observational information.

4. 'Overproduction' of RNe/CNe in the SD Scenario?

Gilfanov & Bogdán (2011) also claimed that the observed number of novae in early-type galaxies is much smaller than that expected from the SD scenario, and suggested that the SD scenario is not the major path to SNe Ia. My criticisms are as follows: (1) They confused the recurrent novae (RNe) and classical novae (CNe); these two are in different binary evolutionary paths. CNe are not the candidates for SNe Ia, so the ratio of observed number of novae and expected number of RNe has no scientific meaning. Moreover, the number of RNe is unknown, but many undetected RNe candidates are suggested by Strope *et al.* (2010). (2) They overestimated the "expected number of RNe" in the SD scenario in the same logic as in Section 2, i.e., all the accreting WDs stay in the RNe phase (not the SSS phase, this time) during their lifetimes. (3) A large part of "recurrent nova" of Figure 1 may not correspond to a typical RN like RS Oph, but may be like UV variables. Because shell flashes are so weak (e.g., Sion & Starrfield 1986), these shell flashes may be very dark in optical wavelengths and not identified as recurrent novae. Considering these uncertainties, one may reduce the statistically expected number of "normal" RNe (like RS Oph) by two orders of magnitude, and the expected number of RNe increases by a factor of 10, which makes Gilfanov & Bogdán's (2011) discrepancy almost vanish.

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