Progenitors of type Ia supernovae in elliptical galaxies

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Abstract. Although there is a nearly universal agreement that type Ia supernovae are associated with the thermonuclear disruption of a CO white dwarf, the exact nature of their progenitors is still unknown. The single degenerate scenario envisages a white dwarf accreting matter from a non-degenerate companion in a binary system. Nuclear energy of the accreted matter is released in the form of electromagnetic radiation or gives rise to numerous classical nova explosions *prior* to the supernova event. We show that combined X-ray output of supernova progenitors and statistics of classical novae predicted in the single degenerate scenario are inconsistent with X-ray and optical observations of nearby early type galaxies and galaxy bulges. White dwarfs accreting from a donor star in a binary system and detonating at the Chandrasekhar mass limit can account for no more than $\sim 5\%$ of type Ia supernovae observed in old stellar populations.

A carbon-oxygen white dwarf (WD) formed through standard stellar evolution can not be more massive than $\approx 1.1 - 1.2 M_\odot$ [22]. Sub-Chandrasekhar models have been unsuccessful so far in reproducing observed properties of type Ia supernovae (SNe Ia) [9, 16], although the effort continues [19]. In order to reach the Chandrasekhar mass of $\approx 1.38 M_\odot$ at least $\Delta M \geq 0.2 M_\odot$ of matter needs to be accreted. Accretion of hydrogen-rich material onto the white dwarf is accompanied by hydrogen fusion on its surface, which is known to be unstable at small values of the mass accretion rate, giving rise to Classical Nova events [17]. Because most of the accreted envelope and some of the original WD material is likely to be lost lost in the nova explosion [20], it is believed that the WD does not grow in mass if nuclear burning is unstable. For this reason steady burning regime is strongly favored by the accretion scenario [e.g. 14].

X-ray constraints

In steady nuclear burning regime, corresponding to the mass accretion rates $\dot{M} \geq 10^{-7} \ M_\odot/\text{yr}$, energy of hydrogen fusion is liberated in the form of electromagnetic radiation, with luminosity of

$$L_{nuc} = \varepsilon_H X \dot{M} \sim 10^{37} \ \text{erg/s}$$

where $\varepsilon_H \approx 6 \cdot 10^{18}$ erg/g is energy release per unit mass and X – hydrogen mass fraction (the solar value of $X = 0.72$ is assumed). The nuclear luminosity exceeds by
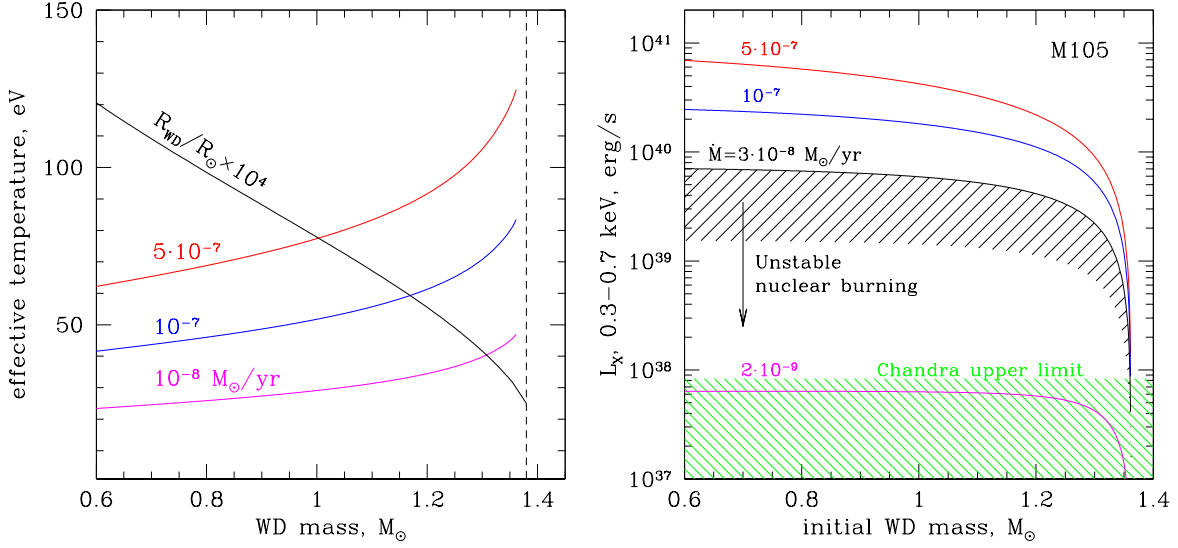
FIGURE 1. *Left:* Dependence of the WD radius [18] and effective temperature of its surface on the WD mass. The effective temperature is computed for 3 different values of the mass accretion rate, assuming steady nuclear burning. *Right:* The expected soft X-ray luminosity of nuclear burning white dwarfs in M105 galaxy assuming that all type Ia supernovae are formed according to the accretion scenario. The solid curves show predicted luminosity as a function of the initial WD mass, assuming that it is same for all SN Ia progenitors and they all have same $\dot{M}$ indicated by the numbers near the curves. The shaded area at the bottom shows the luminosity range compatible with Chandra observations. Its upper bound is an absolute upper limit which includes unresolved emission and combined luminosity of all sources with the color temperature $kT_c \leq 200$ eV [1]. The actual luminosity of accreting WDs is likely by a factor of $\sim 2 - 3$ lower. In the single degenerate scenario plausible SN Ia progenitors have $\dot{M} \geq 10^{-7} M_\odot/yr$ [14]. Below $\sim$ few $\cdot 10^{-8} M_\odot/yr$ CN outbursts will be triggered, which frequency will contradict to observations (Fig.2).

more than an order of magnitude the gravitational energy of accretion, $L_{grav} = GM\dot{M}/R$, and maintains the effective temperature of the WD surface at the level, defined by the Stefan-Boltzmann law:

$$T_{eff} \approx 67 \left(\frac{\dot{M}}{5 \cdot 10^{-7} M_\odot/yr} \right)^{1/4} \left(\frac{R_{WD}}{10^{-2} R_\odot} \right)^{-1/2} \text{eV} \qquad (1)$$

Such a soft spectrum is prone to absorption by interstellar gas and dust, especially at smaller temperatures. Because the WD radius R_{WD} decreases with its mass [18], the T_{eff} increases as the WD approaches the Chandrasekhar limit – the signal, detectable at X-ray wavelengths, will be dominated by the most massive WDs (Fig.1) [6, 5].

The type Ia supernova rate scales with near-infrared luminosity of the host galaxy and for E/S0 galaxies $\dot{N}_{SNIa} \approx 3.5 \cdot 10^{-4}$ yr^{-1} per $10^{10} L_{K,\odot}$ [15]. If the WD mass grows at a rate $\dot{M}$, a population of

$$N_{WD} \sim \frac{\Delta M}{\dot{M} \langle \Delta t \rangle} \sim \frac{\Delta M}{\dot{M}} \dot{N}_{SNIa} \qquad (2)$$

TABLE 1. Comparison of the accretion scenario with observations [6]. X-ray luminosities refer to the soft (0.3–0.7 keV) band. The columns marked "predicted" display total number and combined X-ray luminosity (absorption applied) of accreting WDs in the galaxy predicted in case the single degenerate scenario would produce all SNe Ia. In computing predicted numbers we halved the SN Ia rates as discussed in [6], other parameters are: $\dot{M} = 10^{-7}$ $M_\odot$/yr, initial WD mass $1.2M_\odot$.

Name	L_K [$L_{K,\odot}$] observed	N_{WD} predicted	L_X [erg/s] observed	predicted
M32	$8.5 \cdot 10^8$	25	$1.5 \cdot 10^{36}$	$7.1 \cdot 10^{37}$
NGC3377	$2.0 \cdot 10^{10}$	$5.8 \cdot 10^2$	$4.7 \cdot 10^{37}$	$2.7 \cdot 10^{39}$
M31 bulge	$3.7 \cdot 10^{10}$	$1.1 \cdot 10^3$	$6.3 \cdot 10^{37}$	$2.3 \cdot 10^{39}$
M105	$4.1 \cdot 10^{10}$	$1.2 \cdot 10^3$	$8.3 \cdot 10^{37}$	$5.5 \cdot 10^{39}$
NGC4278	$5.5 \cdot 10^{10}$	$1.6 \cdot 10^3$	$1.5 \cdot 10^{38}$	$7.6 \cdot 10^{39}$
NGC3585	$1.5 \cdot 10^{11}$	$4.4 \cdot 10^3$	$3.8 \cdot 10^{38}$	$1.4 \cdot 10^{40}$

accreting WDs is needed in order for one supernova to explode on average every $\langle \Delta t \rangle = \dot{N}_{SNIa}^{-1}$ years. Thus, for a typical galaxy, the accretion scenario predicts a numerous population of accreting white dwarfs, $N_{WD} \sim \text{few} \times (10^2 - 10^3)$, much more than numbers of soft X-ray sources actually observed [4]. Therefore, although the brightest and hottest of them may indeed reveal themselves as super-soft sources, the vast majority of SN Ia progenitors must remain unresolved or hidden from the observer, for example by interstellar absorption, in order for the accretion scenario to work. Their combined luminosity is

$$L_{tot} = L_{nuc} \times N_{WD} = \varepsilon X \Delta M \dot{N}_{SNIa} \tag{3}$$

where ΔM is the difference between the Chandrasekhar mass and the initial WD mass. Predicted luminosity can be compared with observations, after absorption and bolometric corrections are accounted for.

To this end we collected archival data of X-ray (Chandra) and near-infrared (Spitzer and 2MASS) observations of several nearby gas-poor elliptical galaxies and for the bulge of M31 ([1, 6], Table 1). Using K-band measurements to predict the SN Ia rates, we computed combined X-ray luminosities of SN Ia progenitors expected in the accretion scenario and compared them with Chandra observations. Obviously, the observed values present upper limits on the luminosity of the hypothetical population of accreting WD, as there may be other types of X-ray sources contributing to the observed emission. As is clear from the Table 1, predicted luminosities surpass observed ones by a factor of $\sim 30 - 50$, i.e. the accretion scenario is inconsistent with observations by a large margin.

Statistics of recurrent and classical novae

Unstable nuclear burning at low $\dot{M}$ is not generally believed to allow accumulation of mass, sufficient to lead to supernova explosion. However, just below the stable burning limit a considerable fraction of the envelope mass can be retained by the WD during the nova explosion [20]. This motivated some authors to propose recurrent

novae as supernova progenitors [e.g. 8]. We demonstrate below that such systems will overproduce nova explosions in galaxies.

Assuming that classical/recurrent nova sources are the main type of SN Ia progenitors, one can relate the nova and supernova rates:

$$\Delta M_{acc} \dot{N}_{CN} \sim \Delta M_{SN} \dot{N}_{SN} \tag{4}$$

where $\Delta M_{acc} \leq 10^{-7} - 10^{-4}$ M$_\odot$ is the mass accumulated by the WD per one nova outburst cycle, $\Delta M_{SN} \sim 0.5$ M$_\odot$ is the mass needed for the WD to reach the Chandrasekhar limit. As ΔM_{acc} depends on the $\dot{M}$ and WD mass (Fig.2), we write more precisely:

$$\frac{\dot{N}_{CN}}{\dot{N}_{SNIa}} = \int \frac{dM_{WD}}{\Delta M_{acc}(M_{WD}, \dot{M})} \geq \int \frac{dM_{WD}}{\Delta M_{CN}(M_{WD}, \dot{M})} \tag{5}$$

where ΔM_{CN} is the mass of the hydrogen shell required for the nova outburst to start. The inequality in the eq.(5) follows from the fact that $\Delta M_{acc} \leq \Delta M_{CN}$, due to the possible mass loss during the nova outburst. As the ΔM_{CN} decreases steeply with the WD mass (Fig.2), the main contribution to the predicted CN rate is made by the most massive WDs, similar to X-ray emission in the steady nuclear burning regime. They will be producing frequent outbursts with relatively short decay times [20], thus resulting in a large population of fast (some of them recurrent) novae. This will contradict to the statistics of CNe, as illustrated by the example of M31 shown in Fig.2. Indeed, the observed rate of CN with decay time shorter than 20 days in this galaxy is $\approx 5.2 \pm 1.1$ yr^{-1} [3], while eq.(5) predicts ~ 300 yr^{-1} for the mass accretion rates relevant to the recurrent novae-based progenitors models, $\dot{M} \sim 10^{-8}$ M$_\odot$/yr. As ΔM_{CN} is larger at small $\dot{M}$ (Fig.2), the contradiction between observed and predicted nova frequencies becomes less dramatic at smaller $\dot{M}$. However, very low values of $\dot{M} \ll 10^{-10}$ M$_\odot$/yr are not feasible in the context of SN Ia progenitors. More realistic models with $\dot{M} \geq 10^{-8}$ M$_\odot$/yr do not produce more that $\sim 2\%$ of type Ia supernovae.

Conclusion

Thus, no more than $\sim$few per cent of SNe Ia in early type galaxies can be produced by white dwarfs accreting from a donor star in a binary system and exploding at the Chandrasekhar mass limit. In the steady nuclear burning regime the supernova progenitors would emit too much of soft X-ray emission, while if nuclear burning is unstable they would overproduce classical nova explosions.

At very high $\dot{M}$ the white dwarf could grow in mass without conflicting X-ray constraints or nova statistics, but would do this rather inefficiently, because a significant fraction of the transferred mass is lost in the wind [7, 13]. Therefore a relatively massive (*at least $M \geq 1.3 - 1.7$ M$_\odot$*) donor star is required for the white dwarf to reach the Chandrasekhar limit in this regime. Because the lifetimes of such stars do not exceed $\sim$few Gyr, this mechanism may work only in late-type and in the youngest of early-type galaxies.

As relevance of sub-Chandraskhar models is still debated [9, 16, 19], the only currently viable alternative are WDs mergers [10, 21]. This mechanism may be the main
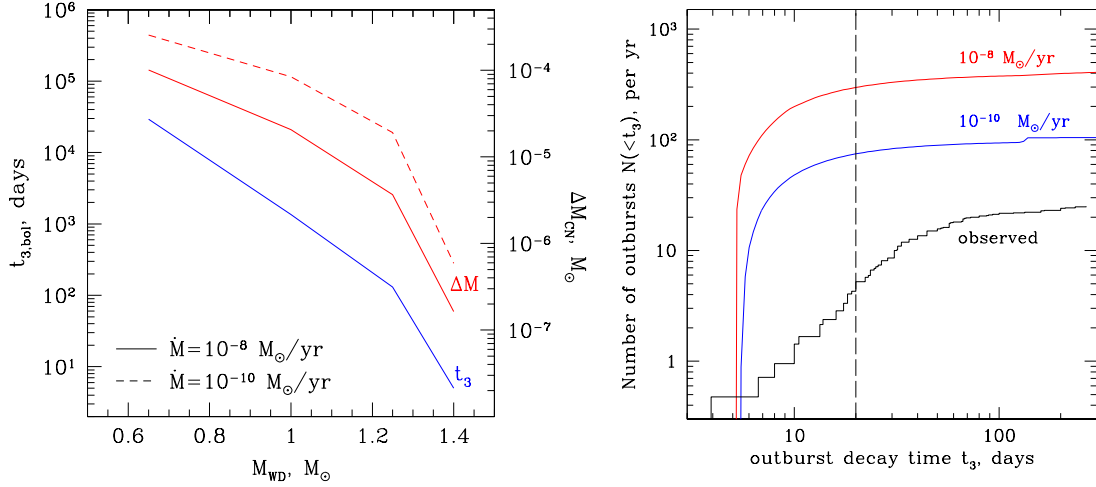
FIGURE 2. *Left:* The $\dot{M}$ and M_{WD} dependence of the nova ignition mass ΔM_{CN} and decay time t_3, from [20]. *Right:* The decay time t_3 distribution for CNe in M31. The histogram shows the observed distribution from [3] normalized to the total rate of 25 CN/yr. The systematic effects may somewhat modify its shape but will not affect our conclusions, as the observations control times do not vary significantly across the t_3 range of interest [3]. Two smooth lines show predicted distributions for two different values of $\dot{M}$. They are computed assuming that cataclysmic variables are the sole progenitors of SN Ia and are based on the results of numerical simulations of CN outburst cycles from [20] for the WD core temperature of 10^7 K. The vertical dashed line denotes the boundary of the fast Novae, which statistics is discussed in the text.

formation channel for SN Ia in early type galaxies. In late-type galaxies, on the contrary, massive donor stars are available, making the mass budget less prohibitive, so that WDs can grow to the Chandrasekhar mass entirely inside an optically thick wind or, via accretion of He-rich material from a He donor star [11]. In addition, a star-forming environment is usually characterized by large amounts of neutral gas and dust, leading to increased absorption obscuring soft X-ray radiation from accreting WDs. Therefore in late-type galaxies the accretion scenario may play a significant role, explaining, for example, the population of prompt supernovae [2].

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