An upper limit on the contribution of accreting white dwarfs to the type la supernova rate

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There is wide agreement that Type Ia supernovae (used as standard candles for cosmology) are associated with the thermonuclear explosions of white dwarf stars.^{1,2} The nuclear runaway that leads to the explosion could start in a white dwarf gradually accumulating matter from a companion star until it reaches the Chandrasekhar limit,³ or could be triggered by the merger of two white dwarfs in a compact binary system.^{4,5} The X-ray signatures of these two possible paths are very different. Whereas no strong electromagnetic emission is expected in the merger scenario until shortly before the supernova, the white dwarf accreting material from the normal star becomes a source of copious X-rays for $\sim 10^7$ yr before the explosion. This offers a means of determining which path dominates. Here we report that the observed X-ray flux from six nearby elliptical galaxies and galaxy bulges is a factor of $\sim 30-50$ less than predicted in the accretion scenario, based upon an estimate of the supernova rate from their K-band luminosities. We conclude that no more than ~ 5 per cent of Type Ia supernovae in early type galaxies can be produced by white dwarfs in accreting binary systems, unless their progenitors are much younger than the bulk of the stellar population in these galaxies, or explosions of sub-Chandrasekhar white dwarfs make a significant contribution

to the supernova rate.

The maximum possible mass of a carbon-oxygen white dwarf formed through standard stellar evolution can not not exceed $\approx 1.1 - 1.2 M_{\odot}$.⁶ Although the nuclear detonation can start below the Chandrasekhar mass ($\approx 1.38 M_{\odot}$), sub-Chandrasekhar models have so far failed to reproduce observed properties of Type Ia supernovae (SNIa),^{7,8} despite continuing effort.⁹ So the white dwarf needs to accreete $\Delta M \gtrsim 0.2 M_{\odot}$ of matter before the supernova explosion happens.

As accreted material accumulates on the white dwarf surface, hydrogen shell burning is ignited, converting hydrogen to helium and, possibly, further to carbon and oxygen. Depending on the mass accretion rate \dot{M} , it may proceed either in a (quasi-) steady regime or explosively, giving rise to Classical Nova events.¹⁰ Because mass is lost in Nova outbursts,¹¹ the white dwarf does not grow if nuclear burning is unstable. For this reason the steady burning regime is strongly preferred by the accretion scenario,² limiting the range of the mass accretion rate relevant to the problem of SNIa progenitors to $\dot{M} \gtrsim 10^{-7} M_{\odot}$ /yr. In this regime energy of hydrogen fusion is released in the form of electromagnetic radiation, with luminosity of $L_{WD,nuc} = \epsilon_H X \dot{M} \sim 10^{37}$ erg/s, where $\epsilon_H \approx 6 \cdot 10^{18}$ 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 more than an order of magnitude the gravitational energy of accretion and maintains the effective temperature of the white dwarf surface at the level (defined by the Stefan-Boltzmann law):

$$T_{eff} \approx 45 \; (\dot{M}/10^{-7} M_{\odot}/yr)^{1/4} (R_{WD}/10^{-2} R_{\odot})^{-1/2} \; eV.$$
 (1)

The black body spectrum of this temperature peaks in the soft X-ray band and, therefore, is prone

to absorption by interstellar gas and dust, especially at the lower end of the temperature range. Because the white dwarf radius R_{WD} decreases with its mass,¹² the T_{eff} increases as the white dwarf approaches the Chandrasekhar limit – the signal, detectable at X-ray wavelengths, will be dominated by the most massive white dwarfs. Such sources are indeed observed in the Milky Way and nearby galaxies and are known as super-soft sources.¹³

The Type Ia supernova rate \dot{N}_{SNIa} scales with stellar mass and, hence, with near-infrared luminosity of the host galaxy.¹⁴ The scale factor is calibrated through extensive observations of nearby galaxies and for E/S0 galaxies equals¹⁴ $\dot{N}_{SNIa}/L_K \approx 3.5 \cdot 10^{-4} \text{ yr}^{-1}$ per $10^{10} L_{K,\odot}$, corresponding to one supernova in a few hundred years for a typical galaxy. If the white dwarf mass increases at a rate \dot{M} , a population of

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

accreting white dwarfs is needed in order for one supernova to explode on average every $\langle \Delta t \rangle = \dot{N}_{SNIa}^{-1}$ years (where ΔM is the difference between the Chandrasekhar mass and the initial white dwarf mass). With $\dot{M} \sim 10^{-7} - 10^{-6} M_{\odot}$ /yr, for a typical galaxy $N_{WD} \sim \text{few} \times (10^2 - 10^3)$ – the accretion scenario predicts a numerous population of accreting white dwarfs. The brightest and hottest of them may reveal themselves as super-soft sources,¹⁵ but the vast majority must remain unresolved or hidden from the observer, for example by interstellar absorption. The combined luminosity of this "sea" of accreting white dwarfs is

$$L_{tot,nuc} = L_{WD,nuc} \times N_{WD} = \epsilon X \Delta M N_{SNIa} \tag{3}$$

Unlike the number of sources, the luminosity allows an accurate account for absorption and bolo-

metric corrections and therefore a quantitative comparison with observations can be made.

We therefore 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 (Table 1). Using K-band measurements to predict the SNIa rates, we computed combined X-ray luminosities of SNIa progenitors, based on a conservative, but plausible choice of parameters: $\dot{M} = 10^{-7} M_{\odot}/\text{yr}$ and initial white dwarf mass of $1.2M_{\odot}$. The SNIa rate was reduced by a half in order to account for the fact that galaxies in our test-sample are somewhat older¹⁶ than those used to derive the rate.¹⁷ In computing the spectral energy distribution we took into account the dependence of the effective temperature on the white dwarf mass according to eq.(1), and the effect of the interstellar absorption (which does not exceed a factor of $\sim 3 - 4$). The X-ray and near-infrared data was prepared and analyzed as described elsewhere.¹⁸ The observed X-ray luminosities were not corrected for absorption and include unresolved emission and emission from resolved compact sources with hardness ratio corresponding to $kT_{bb} \leq 200$ eV. The contribution of warm ionized gas was subtracted, when possible.

Obviously, the observed values present upper limits on the luminosity of the hypothetical population of accreting white dwarf, 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 $\sim 30-50$ demonstrating that the accretion scenario is inconsistent with observations by a large margin.

There exists a maximum rate at which hydrogen can burn on the white dwarf surface, $\dot{M}_{RG} \sim$

 $10^{-6} M_{\odot}/\text{yr}$.¹⁰ The excess material may leave the system in the form of a radiation driven wind¹⁹ or may form a common envelope configuration.^{2,20} In both cases, because of the large photospheric radius, $\sim 10^2 - 10^3 \text{ R}_{\odot}$, the peak of the radiation is in the ultraviolet part of the spectrum and emission from such an object will be virtually undetectable, due to interstellar absorption and dilution with the stellar light. However, there is a nearly universal consensus² that the common envelope configuration does not lead to the type Ia supernova explosion, producing a double white dwarf binary system instead.

In the wind regime, the white dwarf could grow in mass but it is a rather inefficient process because a significant fraction of the transferred mass is lost in the wind.^{19,21} Therefore a relatively massive, $M \gtrsim 1.3 - 1.7 M_{\odot}$, donor star is required in order for the white dwarf to reach the Chandrasekhar limit. As the lifetimes of such stars do not exceed $\sim 2 - 5$ Gyrs, they may exist only in the youngest of early type galaxies, in which no more than $\sim 30-40$ per cent of supernovae are detected.¹⁷ We took this into account in our calculations by halving the canonical value of the type Ia supernova rate¹⁴. On a related note, in many elliptical galaxies small sub-populations of young stars are detected.²² The ages of type Ia supernova progenitors are not very well constrained observationally, so it is possible in principle, that their progenitors are much younger than the bulk of the stellar population. However, given a small fraction of young sub-populations in elliptical galaxies (a few per cent or less), this would imply very high efficiency of young stars in producing supernovae and type Ia supernova rates in spiral galaxies that are too high, much higher than observed.¹⁴ This is therefore not a likely scenario. Thus, in early-type galaxies, white dwarfs accreting from a donor star in a binary system and detonating at the Chandrasekhar limit do not contribute more than about 5 per cent to the observed type Ia supernova rate. At present the only viable alternative is the merger of two white dwarfs, so we conclude that type Ia supernovae in early-type galaxies arise predominantly from the double degenerate scenario. In late-type galaxies, in contrast, massive donor stars are available making the mass budget less prohibitive, so that white dwarfs can grow to the Chandrasekhar mass entirely inside an optically thick wind^{19,21} or via accretion of He-rich material from a He donor star.²³ 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 white dwarfs. Therefore in late-type galaxies the role of the accretion scenario may be significant.

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Table 1: Comparison of the accretion scenario with observations. Listed for each galaxy are: name, K-band luminosity, number of accreting white dwarfs and X-ray luminosities in the soft (0.3–0.7 keV) band. The statistical errors for observed X-ray luminosities range from 20% (NGC 3377) to less than 7%. The columns marked "predicted" display total number and combined X-ray luminosity (absorption applied) of accreting white dwarfs in the galaxy predicted in case the single degenerate scenario would produce all SNeIa. They were computed assuming $\dot{M} = 10^{-7} M_{\odot}$ /yr and initial white dwarf mass of $1.2M_{\odot}$. The N_{WD} drops by a factor of 10 for $\dot{M} = 10^{-6} M_{\odot}$ /yr.

Name	$L_K \left[L_{K,\odot} \right]$	N_{WD}	L_X [erg/s]	
	observed	predicted	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	$3.7\cdot10^{10}$	$1.1 \cdot 10^3$	$6.3\cdot 10^{37}$	$2.3\cdot 10^{39}$
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	$1.5 \cdot 10^{11}$	$4.4 \cdot 10^{3}$	$3.8 \cdot 10^{38}$	$1.4 \cdot 10^{40}$