POSSIBLE WHITE DWARF PROGENITORS OF TYPE Ia SUPERNOVAE

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ABSTRACT

We examine catalogs of white dwarfs (WDs) and find that there are sufficient number of massive WDs, $M_{WD} \gtrsim 1.35 M_\odot$, that might potentially explode as type Ia supernovae (SNe Ia) in the frame of the core degenerate scenario. In the core degenerate scenario, a WD merges with the carbon-oxygen core of a giant star, and they form a massive WD that might explode with a time delay of years to billions of years. If the core degenerate scenario accounts for all SNe Ia, then we calculate that about 0.2 per cent of the present WDs in the Galaxy are massive. Furthermore, we find from the catalogs that the fraction of massive WDs relative to all WDs is about 1-3 per cent, with large uncertainties. Namely, five to ten times the required number. If there are many SNe Ia that result from lower mass WDs, $M_{WD} \lesssim 1.3 M_\odot$, for which another scenario is responsible for, and the core degenerate scenario accounts only for the SNe Ia that explode as massive WDs, then the ratio of observed massive WDs to required is even larger. Despite the several open difficulties of the core degenerate scenario, it is our view that this finding leaves the core degenerate scenario as a possible SN Ia scenario, and possibly even a promising SN Ia scenario.

Keywords: (stars:) white dwarfs, (stars:) supernovae: general

1. INTRODUCTION

There is no consensus on the binary stellar evolutionary route that might bring a white dwarf (WD) to undergo thermonuclear explosion that completely destroys the WD in type Ia supernovae (SNe Ia). A detailed comparison of the different evolutionary routes requires to classify them into five basic scenarios (see table 1 in Soker 2018). We list them (by alphabetical order) as follows (for very recent reviews that discuss the five scenarios and references to many earlier papers and reviews see Livio & Mazzali 2018; Soker 2018; Wang 2018).

(1) In the core-degenerate (CD) scenario a CO WD merges with the core of a massive asymptotic giant branch (AGB) star at the final stages of the common envelope evolution. In the last several years the CD scenario has been developed as a separate SN Ia scenario (e.g., Kashi & Soker 2011; Ilkov & Soker 2013; Aznar-Siguán et al. 2015) that, according to some of these papers, might account for most SNe Ia. On the other hand, conducted a population synthesis study and concluded that this scenario can not result in more than about 20\% of the total SNe Ia. Note that Livio & Rieisl 2003 considered the core-WD merger to be a rare event rather than a separate main SN Ia scenario. (2) In the double degenerate (DD) scenario two WDs merge (e.g., Webbink 1984; Iben & Tutukov 1984) most likely in a violent process (e.g., Pakmor et al. 2010; 2011; Liu et al. 2016) a long time after the common envelope evolution has ended. The time delay from merger to explosion (merger explosion delay, or MED) allowed and required by this scenario is an open question (e.g., Lorén-Águilar et al. 2009; van Kerkwijk et al. 2010; Pakmor et al. 2013; Levanon et al. 2015). (3) In the double detonation (DDet) mechanism a detonation of a helium-rich layer that was accreted from a companion ignites the CO WD (e.g., Woosley & Weaver 1994; Livne & Arnett 1995; Shen et al. 2018). (4) In the single degenerate (SD) scenario. A WD accretes a mass from a non-degenerate companion, reaches a mass close to the Chandrasekhar mass limit ($M_{\text{Ch}}$), and explodes (e.g., Whelan & Iben 1973; Han & Podsiadlowski 2004; Wang et al. 2009). The WD might explode as soon as it reaches close to $M_{\text{Ch}}$, or explode later after it loses some of its angular momentum (e.g., Piersanti et al. 2003; Di Stefano et al. 2011; Justham 2011). (5) The WD-WD collision (WWC) scenario involves the collision of two WDs at about their free fall velocity into each other (e.g., Raskin et al. 2009; Rosswog et al. 2009; Kushnir et al. 2013; Aznar-Siguán et al. 2014). As studies of SNe Ia are generally biased towards one or the other of these scenarios, in many cases papers do not consider all five scenarios, hence might reach questionable conclusions. One example are SNe Ia that interact with circumstellar matter (CSM), so called SNe Ia-CSM. Some papers do not consider the CD scenario for these SNe Ia-CSM, and hence conclude that they results from the SD scenario. This is questionable, as at least for the SN Ia PTF11kx the CD scenario seems to do better than the SD scenario (e.g., Soker et al. 2013). We view it mandatory to mention and consider all five scenarios, and so we listed them above.

As for the explosion mechanism and nuclear yields, a useful classification is to two groups, WDs that explode with masses near the Chandrasekhar mass limit, $M_{\text{Ch}}$, explosions, and WDs that explode with masses below that mass, ‘sub-$M_{\text{Ch}}$ explosions’ (e.g., Maguire et al. 2018). Generally, the CD scenario and the SD scenarios belong to $M_{\text{Ch}}$ explosions, and the DD, DDet, and WWC scenarios belong to the sub-$M_{\text{Ch}}$ explosions.

It is our view that the most promising $M_{\text{Ch}}$ scenario is the CD scenario, and the most promising sub-$M_{\text{Ch}}$ scenario is the DD scenario. The other three scenarios,
according to this view, might account for some peculiar SNe Ia (see Table 1 in [Soker 2018] for the estimated fraction of SNe Ia from each channel). However, this view is far from being in the consensus. Several other alternatives exist, such as the more complex process of the SD scenario where a CO WD accreted helium from a companion (e.g., Wang et al. 2009). Under that view the SD scenario is the main $M_{\text{Ch}}$ scenario.

In a recent paper Ashall et al. (2018) studied two SNe Ia, and concluded that most SNe Ia, including sub-luminous SNe Ia, are consistent with $M_{\text{Ch}}$ delayed-detonation explosions. Since the SD scenario encounters several difficulties, some of them severe (Soker 2018), the results of Ashall et al. (2018) strengthen the CD scenario. Although the CD scenario also suffers from several difficulties, some of them severe (Soker 2018), the CD scenario probably the CD scenario (Soker 2015).

It now seems that any scenario that accounts for all SNe Ia, and indeed Briggs et al. (2018) and references therein) that single WDs that have very strong magnetic fields are not sufficient to account for most SNe Ia, and instead Briggs et al. (2018) did not connect them to SNe Ia.

Several studies have looked for binary WDs that might later experience merger, and some then explode in the frame of the DD scenario (e.g., Badenes & Maoz 2012; Maoz & Hallakoun 2017; Maoz et al. 2015). These studies show that the DD scenario might account mainly for sub-$M_{\text{Ch}}$ explosions. This motivates us to search for the progenitors of $M_{\text{Ch}}$ explosion SNe Ia in the frame of the CD scenario, e.g., single WDs with masses of $M_{\text{WD}} \gtrsim 1.35 M_{\odot}$. We note that a recent study of Gaia observations suggests that there are many WDs that are the result of a merger (Kilic et al. 2018).

In section 2 we estimate the fraction of WDs that we expect to have this high mass. In section 3 we review catalogs of WDs to examine whether there is a potential to find such progenitors. We summarize in section 4.

2. THE EXPECTED FRACTION OF MASSIVE WHITE DWARFS

Following recent studies (Heringer et al. 2017; Friedmann & Maoz 2018) we take the delay time distribution (DTD) to have a slope of $-1.5$ (Heringer et al. 2017) to $-1.3$ (Friedmann & Maoz 2018). Namely, the explosion rate of SNe Ia relative to the total number of WDs that are formed after a star formation episode is

$$\frac{dN}{dt} = \frac{N_0}{t_0} \left( \frac{t}{t_0} \right)^{-\alpha},$$

with $1.3 \lesssim \alpha \lesssim 1.5$. We can estimate the fraction of WDs that we expect to have high mass using two different approaches as follows.

2.1. First approach

Integrating over time gives the fraction of WDs that exploded till time $t$, $N_e(t)$. Integration to infinity gives the fraction of WDs that have exploded as SNe Ia, and concluded that most SNe Ia, including sub-luminous SNe Ia, are consistent with $M_{\text{Ch}}$ delayed-detonation explosions. Since the SD scenario encounters several difficulties, some of them severe (Soker 2018), the results of Ashall et al. (2018) strengthen the CD scenario.

In the second approach we take the explosion rate of SNe Ia, and concluded that most SNe Ia, including sub-luminous SNe Ia, are consistent with $M_{\text{Ch}}$ delayed-detonation explosions. Since the SD scenario encounters several difficulties, some of them severe (Soker 2018), the results of Ashall et al. (2018) strengthen the CD scenario.

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2.2. Second approach

In the second approach we take the explosion rate of SNe Ia during the age of the Galaxy $t_{\text{now}} = 10^{10}$ yr. The average time from star formation to explosion is given by

$$\tau = \frac{\int t N_e dt}{\int N_e dt} = \frac{2 - \alpha}{3 - \alpha} t_{\text{now}} \approx 0.4 \times 10^{10} \text{ yr},$$

where in the first equality we substituted $\alpha = 1.4$ for the DTD slope, and $N_0/(\alpha - 1) = 0.01$ for the total fraction of WDs that explode as SNe Ia over time (larger than the age of the Galaxy).

The typical explosion rate of SN Ia in the galaxy is $dn/dt \approx n/\tau$, where $n$ is the number of SN Ia progenitors. The observed specific rate of SN Ia in our Galaxy is about $n_{\text{obs}} \approx 5.4 \times 10^{-3}$ yr$^{-1}$ (Li et al. 2011; Maoz et al. 2014). Therefore, our expected number of progenitors in the Milky Way is $n \approx \tau n_{\text{obs}} \approx 2 \times 10^{7}$. The total number of WDs in the Galaxy is estimated as $n_{\text{WD}} \approx 1.15 \times 10^{10}$ (table 2 in [Napiwotzki 2009]), from which we derive the expected ratio of progenitors to total number of WD to be $N_{e, G} \approx n/n_{\text{WD}} \approx 0.0018$. This is similar to the value we obtain in equation (1).

The number can be even lower. [Isebrenko & Soker 2015] estimate $\approx 20\%$ of SNe Ia explode inside planetary nebulae (termed SNIP for SN inside planetary nebulae).
If true, then the number of SNe Ia that ‘participate’ in the long time delay is only about 80% of all WDs. This brings the values we derive in the two approaches to be $N_s, G \approx 0.002$ and $N_s, G \approx 0.0015$, respectively. We note that there are large uncertainties. For example, if the number of SNe Ia inside planetary nebulae is lower, then the CD scenario might account for only a fraction of all SNe Ia (e.g., Wang et al. 2017).

We conclude that within the CD scenario, about 0.2% of WDs in the Galaxy should be in a mass of $M_{\text{WD}} \gtrsim 1.35M_\odot$.

Our aim in section 3 is to find whether existing catalogs of WDs have the same fraction of massive WDs as we find theoretically. Namely, that the fraction of WDs with masses of $M_{\text{ED}} \gtrsim 1.35M_\odot$ is larger than about 0.2% of all WDs.

3. STATISTICS FROM CATALOGS

First we find a relation between the log of the WD gravity, $\log g$, and its mass based on two catalogs of WDs from recent years (Kepler et al. 2015, 2016). We present the mass versus $\log g$ from these two catalogs in Fig. 1.

Although duplicates are present between the catalogs we wanted to show the entire data set in order to deduce a trend-line which we will use later. We note that the point of SDSS 155758.90+445636.67 with $\log g = 8.72$ and $M = 0.886M_\odot$, which was our limit, is removed from the sample of Kepler et al. 2015, since clearly the estimated mass is irrelevant.

The trend-line (blue) and Kepler et al. 2015 trend-line (red) in both papers are similar and give $M_{\text{WD}} \approx 1.35$ for $\log g = 9.8$, as we can see directly from the data points. Hence, we empirically assume that values of $\log g \gtrsim 9.8$ result in almost Chandrasekhar mass, when we consider the Montreal WD catalog.

We review the Montreal WD catalog (Dufour et al. 2017) which has 30,768 WDs (as of April 2018). We classify the sample by $\log g$ and by the effective temperature. High effective temperatures can indicate mass accretion and hence either the WDs is in a binary system or it is a young WD. Therefore, cool WDs are more relevant to the CD scenario. In Table 1 we list the number of WDs in different classes, including a separation of single WDs and WDs in binary systems. We make a note of WDs that were found to be in binary systems, marked ‘binary’, and single WDs, marked ‘SU’, in the table. We note that the binary class are known WDs which are in a binary system while the single/unknown (SU) category can not be separated to real single and those that are not determined to be single. Therefore, this class might include WDs in binaries as well. The binary category includes binary systems which are composed of MS and a WD and a few systems which are two WDs. The fraction of WDs with $\log g \gtrsim 9.8$, correspond-

![Fig. 1. Estimated WD mass ($M_\odot$) vs. log($g$/cm s$^{-2}$) from two catalogs for $M_{\text{WD}} \geq 1M_\odot$. We present the catalog of Kepler et al. 2015 with red dots along with a red linear trend-line, and we present the catalog of Kepler et al. 2016 with blue dots along with a blue linear trend-line.](image)

### TABLE 1

| $\log g$ | All   | $\geq 9.5$ | $\geq 9.6$ | $\geq 9.7$ | $\geq 9.8$ | $\geq 9.9$ | $\geq 10$ |
|---------|-------|-----------|-----------|-----------|-----------|-----------|---------|
| All     | 30768 | 541       | 467       | 406       | 368       | 316       | 196     |
| 10$^4$ K| 9281  | 306       | 291       | 283       | 274       | 256       | 173     |
| SU      | 28669 | 476       | 410       | 349       | 311       | 262       | 150     |
| 10$^4$ K| 8750  | 250       | 237       | 229       | 220       | 203       | 127     |
| Binary  | 2099  | 65        | 57        | 57        | 57        | 54        | 46      |
| 10$^4$ K| 531   | 56        | 54        | 54        | 54        | 53        | 46      |
4. SUMMARY

As the community is far from any consensus on the evolutionary routes that brings WDs to explode as SNe Ia (section 1), any study that can shed some light on one or more of the five scenarios is welcome. In the present study we have looked into the question of whether there are enough potential SN Ia progenitors in the frame of the CD scenario.

If the CD scenario accounts for all SNe Ia, then about 0.2% of all WDs in the Galaxy at present should have a mass that will bring the WD to explode, e.g., very close to the limiting Chandrasekhar mass (section 2).

We found from the catalogs of WDs (section 3) that the fraction of WDs with masses of $M_{\text{WD}} \gtrsim 1.35 M_\odot$ is about 1−3%, while the fraction of WDs with masses of $M_{\text{WD}} \gtrsim 1.38 M_\odot$ is about 1%. One must take into account that there are large uncertainties in deriving the value of log $g$, and hence there are large uncertainties in the derived fraction of WDs with the required mass.

Nonetheless, we find that the potential number of massive enough WDs is about 5−10 times the fraction of massive WDs required by the CD scenario. Many of these are WDs rich with Ne, namely ONe WDs. In most cases these will not lead to regular SNe Ia, but rather, most of these WDs end in a collapse to a neutron star, with a minority that might lead to peculiar SNe Ia. We do note that there are suggestions that hybrid CONe WDs do actually lead to regular SNe Ia (e.g., Denis-senkov et al. 2013; Wang et al. 2014), hence further study to better determine the masses of these WDs and their composition is required of course.

If two scenarios or more account for SNe Ia, then the constraint on the number of massive WDs becomes weaker. For example, if the DD scenario accounts for the long time delay from star formation to explosion and for sub-$M_{\text{Ch}}$ explosions, while the CD scenario accounts for $M_{\text{Ch}}$ explosions with shorter time delay, say with about half of SNe Ia coming from each of these two scenarios, then the required fraction of massive WDs progenitors of SNe Ia becomes less than 0.1%. In that case the estimated fraction of massive WDs from observations is more than ten times the required fraction.

We can summarize by stating that despite the several problems and disadvantages of the CD scenario (that include the open questions of, e.g., the long delay from merger to explosion and the ignition process; see Soker [2018]), our main finding leaves the CD scenario as a viable and promising SN Ia scenario.

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