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Common Envelope to Explosion Delay time Distribution (CEEDTD) of Type Ia Supernovae

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Abstract

I use recent observations of circumstellar matter (CSM) around type Ia supernovae (SNe Ia) to estimate the fraction of SNe Ia that explode into a planetary nebula (PN) and to suggest a new delay time distribution from the common envelope evolution (CEE) to the SN Ia explosion for SNe Ia that occur shortly after the CEE. Under the assumption that the CSM results from a CEE, I crudely estimate that about 50% of all SNe Ia are SNe Ia inside PNe (SNIPs), and that the explosions of most SNIPs occur within a CEE to explosion delay (CEED) time of less than about ten thousand years. I also estimate that the explosion rate of SNIPs, i.e., the CEED time distribution, is roughly constant within this timescale of ten thousand years. The short CEED time suggests that a fraction of SNIPs come from the core-degenerate (CD) scenario where the merger of the core with the white dwarf takes place at the end of the CEE. I present my view that the majority of SNIPs come from the CD scenario. I list some further observations that might support or reject my claims, and describe the challenge to theoretical studies to find a process to explain a merger to explosion delay (MED) time of up to ten thousand years or so. A long MED will apply also to the double degenerate scenario.

Key words: (stars:) binaries (including multiple): close – (stars:) white dwarfs – (stars:) supernovae: general – ISM: supernova remnants

1. Introduction

There is neither consensus on the main scenario that triggers white dwarfs (WDs) to ignite thermonuclear explosions as type Ia supernovae (SNe Ia), nor on the classification of the different SN Ia scenarios (e.g., Livio & Mazzali 2018; Wang 2018; Jha et al. 2019; Ruiz-Lapuente 2019; Soker 2019a; Ruiter 2020 for very recent reviews). As most recent studies continue to explore all scenarios (e.g., Livneh & Katz 2020; Pan 2020; Wu et al. 2020; Ablimit 2021; Blondin et al. 2021; Chandra et al. 2021; Clark et al. 2021; Ferrand et al. 2021; Liu et al. 2021; Livneh & Katz 2021; Meng & Luo 2021; Michaely 2021; Patra et al. 2021; Zeng et al. 2021), I briefly review (in alphabetical order) the six binary SN Ia scenarios according to Soker (2019a), where one can find more details. I will not discuss single star scenarios (e.g., Clavelli 2019; Antoniadis et al. 2020).

Before I list these scenarios, I define the merger to explosion delay (MED) time that I introduced in Soker (2018). The MED time is the time from the merger (or mass transfer) event to the explosion itself (more in Section 2.2).

(1) The *core-degenerate (CD) scenario*. In this scenario the merger process of a CO WD (or possibly HeCO WD) with a CO core (or possibly HeCO core) of a massive asymptotic giant branch (AGB) star takes place at the end of the common envelope evolution (CEE) and forms a WD remnant with a mass close to the Chandrasekhar mass limit (e.g., Kashi & Soker 2011; Ilkov & Soker 2013; Aznar-Siguán et al. 2015). In this scenario an MED time is built-in, and exists in all SNe Ia by this scenario. Its value can be $0 < t_{\rm MED} \lesssim 10^{10}$ yr. However, as I argue in the present study (Section 3.3) there is a high SN Ia explosion rate for $t_{\rm MED} \lesssim 10^4$ yr. The largest challenges of the CD scenario are to show that core-WD mergers can lead to a large population of WD remnants with masses close to the Chandrasekhar mass limit, and that these remnants have long MED times. The new study by Neopane et al. (2021) of WD–WD mergers suggests that it is possible to reach these requirements.

(2+3) The *double degenerate (DD) scenarios.* In these scenarios (e.g., Webbink 1984; Iben & Tutukov 1984) the two WDs merge as they lose energy to gravitational waves. One or two of the WDs might be HeCO WDs rather than pure CO WDs (e.g., Yungelson & Kuranov 2017; Perets et al. 2019; Zenati et al. 2019). In the *DD scenario* without MED the explosion is likely to take place during a violent merger process (e.g., Pakmor et al. 2011; Ablimit et al. 2016; Liu et al. 2016). In the *DD-MED scenario* the explosion occurs a long time, more than several months, after the merger process. The value of the MED time is an open question related to the DD scenarios (e.g., Lorén-Aguilar et al. 2009; van Kerkwijk et al. 2010; Pakmor et al. 2013; Levanon et al. 2015; Levanon & Soker 2019).

(4) The *double-detonation (DDet) scenario.* In this scenario the companion transfers helium-rich gas to a CO or a HeCO

WD. The accumulated helium layer ignites and explodes, sending a shock wave into the mass-accreting WD and explodes it (e.g., Woosley & Weaver 1994; Livne & Arnett 1995; Shen et al. 2018). This scenario has no MED time.

(5) The *single degenerate (SD) scenario.* In this scenario the WD accretes hydrogen-rich material from a non-degenerate companion and explodes as a (close to) Chandrasekhar-mass WD (e.g., Whelan & Iben 1973; Han & Podsiadlowski 2004; Wang et al. 2009). It might have no delay time, i.e., it explodes as soon as it reaches the Chandrasekhar mass (or very close to it) or much later after it loses angular momentum (e.g., Piersanti et al. 2003; Di Stefano et al. 2011; Justham 2011), i.e., it has an MED. In the CEE-wind SD scenario (Meng & Podsiadlowski 2017) the explosion might take place shortly after a CEE in case the WD is a hybrid CONe WD (Meng & Podsiadlowski 2018). In my recent review Soker (2019a), I argued that SD-MED, i.e., the SD scenario with MED time, might account for a small fraction of SNe Ia, while in cases of an explosion at the moment the WD becomes close to the Chandrasekhar mass the outcome is a peculiar SN Ia.

(6) The *WD–WD collision (WWC) scenario.* The collision of two WDs with each other at about their freefall velocity triggers an explosion (e.g., Raskin et al. 2009; Rosswog et al. 2009; Kushnir et al. 2013; Aznar-Siguán et al. 2014). Studies argue that this scenario might at best supply <1% of all SNe Ia (e.g., Toonen et al. 2018; Hallakoun & Maoz 2019; Hamers & Thompson 2019). This scenario has no MED time.

Some of the scenarios involve a CEE phase. In those scenarios in addition to the MED time there is the CEE to explosion delay (CEED) time. In Soker (2019b) I introduced the CEE to explosion delay time distribution (CEEDTD), and wrote an approximate expression for it. In the present study I use new observations from the literature (Section 3) to propose a new expression for the CEEDTD (Section 3.3). In deriving this expression I assume that the CSM results from CEE rather than from wind from a giant star or from a mass transfer episode. In Section 4 I summarize the expression for the CEEDTD in the frame of the CD scenario,

2. Definitions of the Delay Times

2.1. The Delay Time Distribution (DTD)

The delay time distribution (DTD) refers to the distribution of the delay time from star formation to the SN Ia explosion

$$t_{\rm SF-E} \equiv \text{Star formation to explosion.} \tag{1}$$

Different groups obtain somewhat different DTDs (e.g., Graur et al. 2014; Heringer et al. 2017; Maoz & Graur 2017; Frohmaier et al. 2019; Wiseman et al. 2021). Here I rely on the same expression as I derived in Soker (2019b) that I based on the DTDs of Friedmann & Maoz (2018) for galaxy clusters and of Heringer et al. (2019) for field galaxies

$$\dot{N}_{\rm DTD} = 0.19 N_{\rm Ia} F_1(t_{\rm i}) \left(\frac{t_{\rm SF-E}}{1\ {\rm Gyr}}\right)^{-1.32} {\rm Gyr}^{-1}, \tag{2}$$

where

$$F_1(t_{\rm i}) = 1.68[(t_{\rm i}/\ {\rm Gyr})^{-0.32} - 13.7^{-0.32}]^{-1}, \tag{3}$$

and SNe Ia occur in the time interval $t_{\rm i} < t_{\rm SF-E} < 13.7$ Gyr. Namely, $t_{\rm i}$ is the first time after star formation when SNe Ia occur.

Friedmann & Maoz (2018) consider $t_{\rm i} = 0.04$ Gyr and find an SN Ia efficiency, i.e., number of SNe Ia per formed stellar mass to be $n_{\rm Ia} \simeq 0.003$–$0.008\ M_\odot^{-1}$. Heringer et al. (2019) have $t_{\rm i} = 0.1$ Gyr and find $n_{\rm Ia} \simeq 0.003$–$0.006\ M_\odot^{-1}$. To proceed I take $t_{\rm i} = 0.05$ Gyr here. This value corresponds to the lifetime of the star with initial mass of $M_{\rm ZAMS} \simeq 6\ M_\odot$ from the main sequence to its AGB phase. Substituting $t_{\rm i} = 0.05$ Gyr in Equations (2) and (3) yields

$$\dot{N}_{\rm DTD} = 0.147 N_{\rm Ia} \left(\frac{t_{\rm SF-E}}{1\ {\rm Gyr}}\right)^{-1.32} {\rm Gyr}^{-1} \quad {\rm for} \quad 0.05\ {\rm Gyr} < t_{\rm SF-E} < 13.7\ {\rm Gyr}. \tag{4}$$

This expression has large uncertainties, but it is not the focus of this study.

I emphasize that the DTD (4) includes *all SNe Ia*, including those with very short delay time after CEE that I discuss below.

2.2. Merger to Explosion Delay (MED) Time

This section is relevant mainly to the CD and DD scenarios that have mergers of two degenerate stars. For the present study I define the MED time as

$$t_{\rm MED} \equiv \text{Merger to explosion.} \tag{5}$$

This time refers also to the time from the termination of the mass transfer to explosion in the SD scenario (Soker 2018), which, however, is not the focus of this study.

In earlier papers (Soker 2018, 2019a, 2019b) I presented arguments stating that many SNe Ia must have a substantial time delay from the merger event to the explosion. The main one is that prompt explosions in the DD scenario lead to highly non-spherical explosions (e.g., Pakmor et al. 2012; Tanikawa et al. 2015; van Rossum et al. 2016; Kashyap et al. 2017), which is in contradiction with the morphology of most SN Ia remnants (SNRs Ia) that tend to be spherical or axisymmetrical (e.g., Lopez et al. 2011). A substantial MED time, i.e., one that is much longer than the dynamical time of the merger process and therefore allows the formation of a single WD, overcomes this challenge. The DDet scenario also leads to non-spherical explosions (e.g., Papish et al. 2015; Tanikawa et al. 2018, 2019), but there is no possibility in the DDet scenario to overcome this challenge as it has no MED time.

2.3. Common Envelope to Explosion Delay (CEED) Time

In Soker (2019b) I listed my motivations to define the CEED time

$$t_{\rm CEED} \equiv \text{End of CEE to explosion.} \quad (6)$$

The first motivation originates from the interaction of the Kepler SNR Ia with massive circumstellar matter (CSM; e.g., Sankrit et al. 2016). The CSM comes from CEE as there are no indications for any giant star that could have blown the CSM (e.g., Kerzendorf et al. 2014; Medan et al. 2017). This suggests that the CSM was blown during CEE in the frame of the CD scenario or that of the DD scenario (Soker 2019b). Meng & Li (2019) propose the CEE-wind channel of the SD scenario for the Kepler SNR, but I will not discuss it here. Another motivation is my view (Soker et al. 2013) that the CSM of the SN PTF11kx is too massive for the SD scenario to account for, beside the CEE-wind channel of the SD scenario (Meng & Podsiadlowski 2018).

In the present study (Section 3.1) I consider new observations of more SNRs Ia that have massive CSM and use these to better constrain the CEED time distribution (CEEDTD).

As the duration of the CEE might be long relative to $t_{\rm MED}$ and $t_{\rm CEED}$ it is important to refer to the starting time of $t_{\rm CEED}$. I take $t_{\rm CEED} = 0$ at the end of the CEE. In the CD scenario this is also the merger time, i.e., in the CD scenario

$$t_{\rm CEED} = t_{\rm MED} \qquad \text{for the CD scenario.} \quad (7)$$

A comment on equality of Equation (7) is appropriate here. In principle the merger can take place before the system ejects the common envelope. However, the merger itself releases a large amount of energy that is likely to eject the entire leftover envelope. In principle the merger might take place after the last amount of bound envelope mass forms a circumbinary disk around the WD-core close binary system (Kashi & Soker 2011). I here consider the phase of the circumbinary disk to be part of the CEE. Overall, the most likely case is that the core-WD merger takes place at the same time as the termination of the CEE.

In the DD scenario the time from the end of the CEE to explosion includes the time to merger due to gravitational waves plus the MED time

$$t_{\rm CEED} = t_{\rm GW} + t_{\rm MED} \qquad \text{for the DD scenario.} \quad (8)$$

3. The SN Ia Rate Shortly After the CEE

3.1. The Fraction of SNe Ia Inside PNe (SNIPs)

3.1.1. Previous Estimates

Tsebrenko & Soker (2015) assumed that the presence of two opposite protrusions from the main shell of an SNR Ia, termed "Ears", indicates that the ejecta interacts with CSM that once was a planetary nebula (PN) (see also Chiotellis et al. 2016). Tsebrenko & Soker (2015) assumed that the ears are along the symmetry axis, i.e., polar ears, and named these SNe Ia SNIPs, for SNe inside PNe, including also SNe Ia explosions inside proto-PNe (Cikota et al. 2017). I note that Chiotellis et al. (2021) study a model where the ears are in the equatorial plane rather than at the polar directions of the SNR. Tsebrenko & Soker (2015) examined the morphology of 13 SNRs and from that estimated that SNIPs amount to at least $\simeq 20\% \pm 10\%$ of all SNe Ia. They derived this number from their estimate, by the presence of ears, that two SNRs Ia posses ears while four other SNRs Ia might posses ears. I list these SNRs in Table 1, indicating the classification of Tsebrenko & Soker (2015) in the third row.

I add two SNe Ia to the list of Tsebrenko & Soker (2015), DEM L249 and DEM L238 (bottom row of Table 1), that I take from Borkowski et al. (2006). Borkowski et al. (2006) suggest the presence of substantial amounts of dense circumstellar gas at the explosions of these two SNe Ia, and that these SNe Ia could be remnants of prompt SNe Ia, i.e., within $\simeq 10^8$ yr from star formation. Based on this estimated dense CSM and the morphologies, I consider these SNe Ia to be SNIPs.

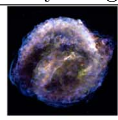
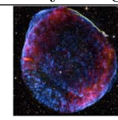
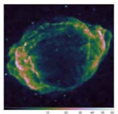
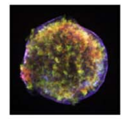
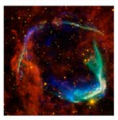
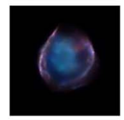
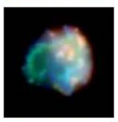
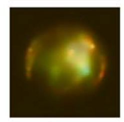
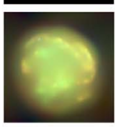
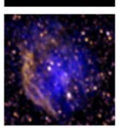
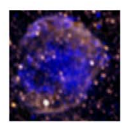
In Soker (2019b) I noted that the SNR Ia N103B does interact with CSM (e.g., Williams et al. 2018). I still estimated the fraction of SNIP as $f_{\rm SNIP} \simeq 15\%$–20%. I further assumed that the time delay to SN Ia explosion during which we can detect an interaction with CSM is $t < t_{\rm SNIP} \simeq 3 \times 10^5$ yr. From that I derive the average SN Ia rate in the time period $0 < t_{\rm CEED} < 3 \times 10^5$ to be $\approx(100$–$1000) N_{\rm Ia}\,{\rm Gyr}^{-1}$. Below I use new observational results to estimate a much higher rate, due both to a larger fraction of SNIPs and to a shorter relevant ejecta-CSM interaction time.

3.1.2. New Estimates of SNIP Fraction

Li et al. (2021) present a study of SNe Ia with Balmer-dominated shells in the Large Magellanic Cloud (LMC). One of them is N103B that has a CSM mass of about 1–3 $M_\odot$ (e.g., Williams et al. 2014; Li et al. 2017; Blair et al. 2020). Li et al. (2021) find that the LMC SNRs Ia N103B, DEML71 and 0548 −70.4 have numerous and wide-spread knots (for DEML71, see also Alan & Bilir 2022), and that their density is too high to originate from an interstellar medium (ISM) source. These high-density knots most-likely originate from a CSM gas. The LMC SNR Ia 0519−69.0 has a small number of knots. There are other indications for the presence of CSM around some SNe Ia, e.g., by the presence of sodium absorption lines (e.g., Patat et al. 2007; Sternberg et al. 2011). For these cases as well, it seems that the CSM is too massive for the SD scenario and better fits the expectations of the CD scenario (e.g., Soker 2015).

Based on the new study of Li et al. (2021), I consider the possibility that the other SNRs Ia that have Balmer-dominated spectra also have a massive CSM, namely, be SNIPs. These are Tycho (Kirshner & Chevalier 1978), SN 1006 (Schweizer &

Table 1
Known Well-resolved SNRs with Ages less than 10,000 yr (based on Tsebrenko & Soker 2015, Beside the two SNe Ia in the Bottom Row)

SNR	X-ray Image	'Ears'	This study	SNR	X-ray Image	'Ears'	This study
Kepler		Yes	Yes (Ears + CSM)	SN 1006		No	Yes (CSM)
G1.9+0.3		Yes	Yes (Ears)	3C 397		No	Maybe
G299.2-2.9		Maybe	Yes (Ears)	Tycho		No	Maybe (CSM)
RCW86		No	Yes (Ears + CSM)	DEM L71		Maybe	Yes (Ears + CSM)
N 103B		No	Yes (CSM)	0548-70.4		No	Yes (Ears + CSM)
0534−69.9		Maybe	Maybe (Ears)	0509-67.5		No	No
0519-69.0		Maybe	Yes (CSM)	—	—	—	—
DEM L249		—	Yes (CSM)	DEM L238		—	Yes (CSM)

Note. The third column is the classification by Tsebrenko & Soker (2015) of whether the SNR is an SNIP (an SN Ia inside a PN) or not, according to the presence or not of "ears", i.e., two opposite protrusions. The fourth column lists my new estimate in the present study of whether the SNR is an SNIP or not. The images are from the Chandra SNR Catalog (references therein).

Lasker 1978), Kepler (Fesen et al. 1989) and RCW86 (Long & Blair 1990). As Tycho has a global spherically symmetric morphology, I mark it as maybe being an SNIP. Of course, not all SNe Ia have CSM (e.g., Cendes et al. 2020). With the two additions to the table (bottom row of Table 1), 11–14 out of 15 SNRs Ia are SNIPs.

From my assessment that 11 out of 15 SNRs Ia are SNIPs and that 3 are "maybe", my new estimate is that in the Galaxy and in the LMC the SNIP fraction is $11/15$ to $(11+3/2)/15$, or

$$f_{\rm SNIP}\,({\rm MW}+{\rm LMC}) \simeq 0.7 - 0.8. \tag{9}$$

However, Table 1 overestimates the fraction of SNIPs for several reasons. (1) SNIPs have a large amount of CSM, which implies that the interaction of the SN Ia ejecta with the CSM makes the SNR brighter, in X-ray, radio and optical, and hence easier to detect. Namely, we might miss some non-SNIP SNRs Ia. (2) The CSM slows down the expansion of the ejecta. This implies that SNIPs can be detected for a longer time. (3) The Galaxy and LMC have on-going star formation so I expect a large fraction of SNe Ia with short time delay from star formation, which in the present study implies a large fraction of SNe Ia with short CEED time, i.e., SNIPs. The fraction of SNIPs when we include elliptical galaxies with lower star formation rates is lower. If SNIPs come from near-Chandrasekhar-mass SNe Ia as I claim here, the higher fraction of SNIPs in star-forming galaxies might be compatible with the finding of Kobayashi et al. (2020) that the fraction of near-Chandrasekhar-mass SNe Ia in the Milky Way is higher than in dwarf galaxies. Brown et al. (2019) find that the specific SN Ia rate is much larger in low-mass galaxies than in massive galaxies. This might also point to a very large fraction of SNe Ia shortly after star formation as the low-mass galaxies have a higher specific star formation rate. Smith et al. (2012), for example, argued that the SN Ia rate per unit stellar mass is a positive function of specific star formation rate.

Because of the large uncertainties in the degree by which the three effects cause Table 1, as expressed in Equation (9), to overestimate the SNIP fraction, I simply take

$$f_{\rm SNIP}\,({\rm total}) \simeq 0.5. \tag{10}$$

If all SNe Ia that take place shortly (see Section 2.3) after star formation are SNIPs, then from the DTD in Equation (4) I find that SNe Ia are SNIPs in the time range of $0.05\,{\rm Gyr} < t_{\rm SF-E} < 0.27\,{\rm Gyr}$. This time span approximately corresponds to stars with zero age main sequence masses in the range of

$$3.5\,M_\odot \lesssim M_{\rm ZAMS} \lesssim 6\,M_\odot \qquad \text{SNIP progenitors.} \tag{11}$$

This range of not-too-low-mass progenitors ensures that in many cases a WD companion merges with the core of an AGB star during the CEE (e.g., Soker et al. 2013; Ablimit et al. 2021). A WD-core merger does not take place at the right time in all cases. In some cases mass transfer can be stable, or it might take place at very early evolutionary phases, like during the Hertzsprung Gap (e.g., Hachisu et al. 2008; Meng & Podsiadlowski 2017). I assume there are sufficiently a large number of systems to account for SNIPs that do merge at the right time (e.g., Soker et al. 2013).

3.2. Estimating the CEED Time

The high mass loss rate at the end of the AGB might be long, up to $\approx 10^5$ yr (e.g., Corradi et al. 2003; Michaely & Perets 2019; Igoshev et al. 2020; Santander-García et al. 2021). I quantify the relevant times from the study by Corradi et al. (2003) of halos of PNe. In PNe with halos, the ages of most halos are in the general range of $t_{\rm halo} \simeq 2\times 10^4$–$8\times 10^4$ yr, while the much more non-spherical inner parts of these PNe, which were formed by the CEE process, have ages in the general range of $t_{\rm neb} \simeq 2\times 10^3$–$10^4$ yr. Corradi et al. (2003) calculate the ages of the halos by assuming an expansion velocity of $v_{\rm halo} = 15\,{\rm km\,s^{-1}}$. Namely, the radii of the halos are in the general range of $r_{\rm halo} \simeq 0.3$–1.2 pc, but one halo extends to 2 pc. The young inner parts imply that, at the termination of the CEE, the outer parts of the halo are at $\simeq 1$ pc.

The distances from the center (explosion site) of the dense knots that Li et al. (2021) attribute to CSM in their new study of four SNe Ia are $r_{\rm knots} \simeq 1$–10 pc. As the AGB progenitor stars that engulf their WD companion are massive (Equation (11)), it is indeed possible that some halos will be very large at the time of explosion. The explosion itself can be a short time after the termination of the CEE, as the halo is already large. I take the explosions that form SNIPs to be within the timescale of

$$t_{\rm SNIP} \approx 10^4\ {\rm yr} \tag{12}$$

after the CEE. This is much shorter than the time I assumed in Soker (2019b) which was 3×10^5 yr.

From Equations (10) and (12) I find the average explosion rate of SNIPs to crudely be

$$\bar{\dot{N}}_{\rm SNIP} = \frac{f_{\rm SNIP}\,N_{\rm Ia}}{t_{\rm SNIP}} \approx 5\times 10^4\,N_{\rm Ia}\ {\rm Gyr^{-1}}. \tag{13}$$

This rate is 50–500 larger than the rate I estimated in Soker (2019b). The new value is motivated to large part by the new results of Li et al. (2021).

There are other supporting indications. Although the delay time from CEE to explosion might be in the frame of the CD scenario (where $t_{\rm CEED} = t_{\rm MED}$; Equation (7)), or in the frame of the DD scenario (where Equation (8) holds) or in the frame of the DDet scenario, due to the short time for gravitational waves to operate I assume that most SNIPs in Table 1 are due to the CD scenario. As well, there is no definitive evidence for surviving companion stars as expected in the DDet and the SD scenarios (e.g., Litke et al. 2017; Li et al. 2019). The non-detection of companions in the SNIPs that I study rule out the process by which a binary system in the frame of the SD scenario experiences a delayed dynamical instability that leads to a high mass loss rate, a scenario proposed by Han & Podsiadlowski (2006).

The CD scenario implies that after core-WD merger most merger remnants live for up to $t_{\rm SNIP} \approx 10^4$ yr before they explode. The lifetime of many merger products might be much larger though. The merger remnant is a WD of about the Chandrasekhar mass. This implies the existence of a non-negligible population of WDs with masses close to the Chandrasekhar mass limit. In Bear & Soker (2018) we examined catalogs of WDs and concluded that there is a sufficient number of massive ($M_{\rm WD} \gtrsim 1.35\ M_\odot$) WDs that might potentially explode as SNe Ia in the frame of the CD scenario. In a very recent study, Caiazzo et al. (2021) report the discovery of a magnetized WD with a mass of $>1.35\ M_\odot$ and argue, along the earlier claim of Bear & Soker (2018), that such objects are not rare.

3.3. Estimating the CEED Time Distribution (CEEDTD)

SNe Ia-CSM are a rare (e.g., Szalai et al. 2019; Dubay et al. 2021) class of SNe Ia that interact with close CSM, i.e., at $R_{\rm CSM} \lesssim 10^{17}$ cm, such as PTF11kx (Dilday et al. 2012) and SN 2015cp (Graham et al. 2019). In Soker (2019b) I took a CSM expansion velocity of $10\,{\rm km\,s^{-1}}$, and I assumed that this CSM was formed during the CEE. From these, I estimate the

CEED time of SNe Ia-CSM to be $t_{\rm CSM} \lesssim 3000$ yr. However, considering the presence of halos in PNe (Section 3.2), this time can be shorter. I take here $t_{\rm CSM} \lesssim 1000$ yr. I do note that the uncertainty is large. For example, if the inner boundary of the ejected common envelope is from a circumbinary equatorial outflow it might be slower, making the timescale longer. Here, I follow my earlier assumption of an expansion velocity of $10\ {\rm km\ s^{-1}}$. I then adopt the estimate of Graham et al. (2019) that the fraction of SNe Ia-CSM from all SNe Ia is $f_{\rm CSM} < 0.06$. I estimate a similar value from the results of Dubay et al. (2021). For example, for the moderate-luminosity ejecta-CSM interaction, Dubay et al. (2021) estimate the fraction of SNe Ia-CSM that have interaction at 0–500 days [500–1000 days] after discovery to be $f_{\rm CSM} \lesssim 0.073$ [$f_{\rm CSM} \lesssim 0.031$]. In a recent study Sharma et al. (2021) find the fraction of SNe-CSM for CSM within a radius of 0.5×10^{16}–10^{16} cm to be about 1 event per 300 SNe Ia. Scaling to a radius of 10^{17} cm gives a rate of 10–20 in 300, or $\approx$0.03–0.07. From these three studies I take $f_{\rm CSM} \approx 0.05$. This gives the rate of SNe Ia-CSM as

$$\bar{\dot{N}}_{\rm CSM} = \frac{f_{\rm CSM} N_{\rm Ia}}{t_{\rm CSM}} \approx 5 \times 10^4\ N_{\rm Ia}\ {\rm Gyr}^{-1}. \quad (14)$$

Note that the SNe Ia-CSM are part of the SNIPs. Namely, the fraction of $f_{\rm CSM} \approx 0.05$ is part of the fraction given in Equation (10) and not in addition to it.

A comment is in place here about the inner radius of the CSM. After core-WD merger the WD merger remnant is most likely to blow a very fast and tenuous wind as in young (up to several thousand years) PNe. This wind forms a very low density bubble that for hundreds of years accelerates the previously ejected slow wind (e.g., Volk & Kwok 1985). The inner CSM boundary might reach a velocity of $\approx$30–50 km s^{-1}, and in 1000–10,000 yr a radius of $\approx 10^{17}$–$1.5 \times 10^{18}\ {\rm cm} =$ 0.03–0.5 pc.

Because in Soker (2019b) my estimates were that $\bar{\dot{N}}_{\rm CSM} \gg \bar{\dot{N}}_{\rm SNIP}$, I found that crudely the rate of SNe Ia shortly after the CEE decreases as $\approx t^{-1}$. However, in this study I find $\bar{\dot{N}}_{\rm CSM} \approx \bar{\dot{N}}_{\rm SNIP}$ (Equations (13) and 14). This brings me to the main result of this study which is a new estimate of the CEED time distribution (CEEDTD) shortly after the CEE

$$\dot{N}_{\rm Ia,short} \approx 5 \times 10^4\ N_{\rm Ia}\ {\rm Gyr}^{-1} \quad {\rm for} \quad t_{\rm CEED} \lesssim 10^4\ {\rm yr}. \quad (15)$$

The following comments are in place here regarding the CEEDTD of Equation (15).

1. The short CEED time ($t_{\rm CEED} \lesssim 10^4$ yr) means that the expression (15) refers to SNe Ia that take place inside PNe, i.e., SNIPs. This also includes SNe Ia-CSM.
2. The total number of SNe Ia that the short CEEDTD in Equation (15) refers to is $\approx 0.5 N_{\rm Ia}$. This is part of the total number of SNe Ia that the DTD in Equation (4) refers to. Namely, the number of SNe Ia that might take place within a time of $t_{\rm CEED} \lesssim 10^4$ yr from the CEE, with large uncertainties, crudely equals the number of SNe Ia with much larger CEED times.
3. The different dependence on time of the DTD (Equation (4)) and of the CEEDTD (Equation (15)) is not in contradiction because the time in the DTD is measured from star formation, $t_{\rm SF-E}$, and it is a fit over a very long time of $\simeq$10 Gyr, while in the CEEDTD the time is measured from the termination of the CEE.
4. The short CEEDTD (Equation (15)) also predicts an explosion within a short time after merger, possibly even before the common envelope is ejected to large distances ($r \gtrsim 10^{14}$ cm), hence forming a peculiar type II supernova. However, these are very rare.
5. The short CEEDTD (Equation (15)) holds for SN Ia scenarios that require a CEE phase followed by strong interaction or merger, i.e., the CD, DD and DDet scenarios. However, because of the very short time relative to orbital decay due to the emission of gravitational waves, I consider the CD scenario as the dominant one for SNe Ia with short CEED times.
6. If these SNIPs result from the CD scenario it implies that core-WD merger forms WD remnants that are close to the Chandrasekhar mass limit and explode only after a time of up to $\approx 10^4$ yr. This challenges theoretical studies to come up with a mechanism to delay explosion for such timescales, and possibly to much longer timescales but at a decreasing explosion rate. Most likely this mechanism is applicable also to the DD scenario.

4. Summary

The new measurements of dense CSM in four SNe Ia in the LMC (Li et al. 2021) brought me to reassess the fraction of SNe Ia inside PNe, i.e., SNIPs. Based on the morphological features of two opposite "ears" and the presence of massive CSM (fourth row of Table 1), I estimated this fraction to be $\approx$50% of all SNe Ia (Equation (10)). This is about twice as large as in an earlier study of the CEEDTD (Soker 2019b). By comparing the sizes of the CSM of these SNe Ia with the sizes of halos of some PNe I further estimated that the SN Ia explosions in these and similar SNe Ia took place within a time of $t < t_{\rm SNIP} \simeq 10^4$ yr after the end of the CEE. This is about 30 times shorter than my previous estimate in Soker (2019b). From these I estimated the rate of SNIPs as I give in Equation (13), and found it to be similar to the rate of SNe Ia that interact with close CSM, termed SNe Ia-CSM, as I gave in Equation (14). I used these two about equal rates to suggest a new CEEDTD in Equation (15).

Equation (15) that describes my new estimate of the DTD of SNe Ia that occur shortly after the termination of the CEE, i.e., the CEEDTD, is the main result of this study. The number of such short-CEEDTD SNe Ia amounts to about half of all SNe

Ia. As the time delay is short relative to the time of inspiral due to emission of gravitational waves that the DD scenario requires, I claim that the majority, and even all, SNIPs come from the CD scenario.

The new observations that lead to the new expression for the CEEDTD in Equation (15) seem to suggest that a non-negligible fraction of SNe Ia comes from the CD scenario. There are some recent observational suggestions for the CD scenario (e.g., Hsiao et al. 2020; Ashall et al. 2021). Lu et al. (2021), for example, suggest that the under-luminous SN Ia ASASSN-15hy comes from the CD scenario, and Kasuga et al. (2021) further mention that the Kepler SNR might have come from the CD scenario. I find that the new observations of SN 2011fe by Tucker et al. (2021) that reveal the decay of ^{55}Fe support the CD scenario for SN 2011fe (Soker et al. 2014), although the DD-MED scenario can also account for SN 2011fe. As well, some theoretical studies continue to explore the CD scenario for regular and peculiar SNe Ia (e.g., Ablimit 2021)

My new claims require further theoretical studies and more observational tests. The main theoretical task is to show that some core-WD merger (or WD–WD merger) remnants can live for at least up to $\approx 10^4$ yr before they explode. Even longer MED times are possible, but then with decreasing explosion rate. The new study by Neopane et al. (2021) is very encouraging. They argue that (1) WD–WD mergers produce a substantial population within a narrow mass range close to the Chandrasekhar mass limit, and (2) the MED time might be as long as $\approx$100 yr or more (see also Ilkov & Soker 2012). The next theoretical stage would be to improve the core-WD numerical simulations of Aznar-Siguán et al. (2015) and to show that this merger process can also lead to a large population of WDs with masses close to the Chandrasekhar mass limit as the CD scenario requires (e.g., Ilkov & Soker 2013) and try to reach MED times of at least up to $t_{\rm CEED} = t_{\rm MED} \approx 10^4$ yr. Note that the CD scenario allows also for much longer $t_{\rm MED}$ (Ilkov & Soker 2012), in addition to the short $t_{\rm MED}$ that is the focus of this study.

Observations can also support or reject my new suggestion for the CEEDTD. The present results suggest, for example, that $\approx$50% of all SNe Ia should experience ejecta-CSM interaction within $t \lesssim 30$–100 yr of explosion. This interaction might lead to a re-brightening in different bands, e.g., optical and ultraviolet (e.g., Graham et al. 2019), and X-ray and radio. This calls for a long-time monitoring of SNe Ia. As I commented in Soker (2019b) the CSM might contain large amounts of dust that by light reflection can cause re-brightening months to years after the explosion. Maund (2019) raised the possibility that the few years post-explosion delayed re-brightening of the type IIb SN 2011dh might come from a light echo. In SNe Ia the dust mass is lower than in core collapse supernovae, and so the re-brightening will be faint. Some SNe Ia do indeed show light echo (e.g., Graur 2019). The CD scenario suggests that in some cases the echoing dust will have elliptical and bipolar morphologies as many PNe do, although in most cases the halos are more spherical (e.g., Corradi et al. 2003).

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References

Ablimit, I. 2021, PASP, 133, 074201
Ablimit, I., Maeda, K., & Li, X.-D. 2016, ApJ, 826, 53
Ablimit, I., Podsiadlowski, P., Hirai, R., & Wicker, J. 2021, arXiv:2108.08430
Alan, N., & Bilir, S. 2022, MNRAS
Antoniadis, J., Chanlaridis, S., Gräfener, G., & Langer, N. 2020, A&A, 635, A72
Ashall, C., Lu, J., Hsiao, E. Y., et al. 2021, arXiv:2106.12140
Aznar-Siguán, G., García-Berro, E., Lorén-Aguilar, P., Soker, N., & Kashi, A. 2015, MNRAS, 450, 2948
Aznar-Siguán, G., García-Berro, E., Magnien, M., & Lorén-Aguilar, P. 2014, MNRAS, 443, 2372
Bear, E., & Soker, N. 2018, MNRAS, 480, 3702
Blair, W. P., Ghavamian, P., Raymond, J. C., et al. 2020, ApJ, 902, 153
Blondin, S., Bravo, E., Timmes, F., Dessart, L., & Hillier, D. J. 2021, arXiv:2109.13840
Borkowski, K. J., Hendrick, S. P., & Reynolds, S. P. 2006, ApJ, 652, 1259
Brown, J. S., Stanek, K. Z., Holoien, T. W.-S., et al. 2019, MNRAS, 484, 3785
Caiazzo, I., Burdge, K. B., Fuller, J., et al. 2021, Natur, 595, 39
Cendes, Y., Drout, M. R., Chomiuk, L., & Sarbadhicary, S. K. 2020, ApJ, 894, 39
Chandra, V., Hwang, H.-C., Zakamska, N. L., et al. 2021, arXiv:2110.06935
Chiotellis, A., Boumis, P., & Spetsieri, Z. T. 2021, MNRAS, 502, 176
Chiotellis, A., Boumis, P., Walg, S., et al. 2016, in Supernova Remnants: An Odyssey in Space After Stellar Death, 125
Cikota, A., Patat, F., Cikota, S., Spyromilio, J., & Rau, G. 2017, MNRAS, 471, 2111
Clark, P., Maguire, K., Bulla, M., et al. 2021, MNRAS, 507, 4367
Clavelli, L. 2019, arXiv:1908.11397
Corradi, R. L. M., Schönberner, D., Steffen, M., & Perinotto, M. 2003, MNRAS, 340, 417
Di Stefano, R., Voss, R., & Claeys, J. S. W. 2011, ApJL, 738, LL1
Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, Sci, 337, 942
Dubay, L. O., Tucker, M. A., Do, A., Shappee, B. J., & Anand, G. S. 2021, arXiv:2104.02086
Ferrand, G., Warren, D. C., Ono, M., et al. 2021, ApJ, 906, 93
Fesen, R. A., Becker, R. H., Blair, W. P., & Long, K. S. 1989, ApJL, 338, L13
Friedmann, M., & Maoz, D. 2018, MNRAS, 479, 3563
Frohmaier, C., Sullivan, M., Nugent, P. E., et al. 2019, MNRAS, 486, 2308
Graham, M. L., Harris, C. E., Nugent, P. E., et al. 2019, ApJ, 871, 62
Graur, O. 2019, ApJ, 870, 14
Graur, O., Rodney, S. A., Maoz, D., et al. 2014, ApJ, 783, 28
Hachisu, I., Kato, M., & Nomoto, K. 2008, ApJ, 679, 1390
Hallakoun, N., & Maoz, D. 2019, MNRAS, 490, 657
Hamers, A. S., & Thompson, T. A. 2019, ApJ, 882, 24
Han, Z., & Podsiadlowski, P. 2004, MNRAS, 350, 1301
Han, Z., & Podsiadlowski, P. 2006, MNRAS, 368, 1095
Heringer, E., Pritchet, C., Kezwer, J., et al. 2017, ApJ, 834, 15
Heringer, E., Pritchet, C., & van Kerkwijk, M. H. 2019, ApJ, 882, 52
Hsiao, E. Y., Hoeflich, P., Ashall, C., et al. 2020, ApJ, 900, 140
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
Igoshev, A. P., Perets, H. B., & Michaely, E. 2020, MNRAS, 494, 1448
Ilkov, M., & Soker, N. 2012, MNRAS, 419, 1695
Ilkov, M., & Soker, N. 2013, MNRAS, 428, 579
Jha, S. W., Maguire, K., & Sullivan, M. 2019, NatAs, 3, 706

Justham, S. 2011, ApJL, 730, L34
Kashi, A., & Soker, N. 2011, MNRAS, 417, 1466
Kashyap, R., Fisher, R., García-Berro, E., et al. 2017, ApJ, 840, 16
Kasuga, T., Vink, J., Katsuda, S., et al. 2021, ApJ, 915, 42
Kerzendorf, W. E., Childress, M., Scharwächter, J., Do, T., & Schmidt, B. P. 2014, ApJ, 782, 27
Kirshner, R. P., & Chevalier, R. A. 1978, A&A, 67, 267
Kobayashi, C., Leung, S.-C., & Nomoto, K. 2020, ApJ, 895, 138
Kushnir, D., Katz, B., Dong, S., Livne, E., & Fernández, R. 2013, ApJL, 778, L37
Levanon, N., & Soker, N. 2019, ApJL, 872, L7
Levanon, N., Soker, N., & García-Berro, E. 2015, MNRAS, 447, 2803
Li, C.-J., Chu, Y.-H., Gruendl, R. A., et al. 2017, ApJ, 836, 85
Li, C.-J., Chu, Y.-H., Raymond, J. C., et al. 2021, arXiv:2110.09250
Li, C.-J., Kerzendorf, W. E., Chu, Y.-H., et al. 2019, ApJ, 886, 99
Litke, K. C., Chu, Y.-H., Holmes, A., et al. 2017, ApJ, 837, 111
Liu, D.-D., Wang, B., Podsiadlowski, P., & Han, Z. 2016, MNRAS, 461, 3653
Liu, Z.-W., Röpke, F. K., Zeng, Y., & Heger, A. 2021, A&A, 654, A103
Livio, M., & Mazzali, P. 2018, PhR, 736, 1
Livne, E., & Arnett, D. 1995, ApJ, 452, 62
Livneh, R., & Katz, B. 2020, MNRAS, 494, 5811
Livneh, R., & Katz, B. 2021, arXiv:2109.10371
Long, K. S., & Blair, W. P. 1990, ApJL, 358, L13
Lopez, L. A., Ramirez-Ruiz, E., Huppenkothen, D., Badenes, C., & Pooley, D. A. 2011, ApJ, 732, 114
Lorén-Aguilar, P., Isern, J., & García-Berro, E. 2009, A&A, 500, 1193
Lu, J., Ashall, C., Hsiao, E. Y., et al. 2021, ApJ, 920, 107
Maoz, D., & Graur, O. 2017, ApJ, 848, 25
Maund, J. R. 2019, ApJ, 883, 86
Medan, I., Sankrit, R., Blair, W. P., et al. 2017, AAS Meeting Abstracts, 230, 318.12
Meng, X., & Li, J. 2019, MNRAS, 482, 5651
Meng, X., & Podsiadlowski, P. 2017, MNRAS, 469, 4763
Meng, X., & Podsiadlowski, P. 2018, ApJ, 861, 127
Meng, X.-C., & Luo, Y.-P. 2021, MNRAS, 507, 4603
Michaely, E. 2021, MNRAS, 500, 5543
Michaely, E., & Perets, H. B. 2019, MNRAS, 484, 4711
Neopane, S., Bhargava, K., Fisher, R., et al. 2021, arXiv:2111.09890
Pakmor, R., Hachinger, S., Röpke, F. K., & Hillebrandt, W. 2011, A&A, 528, A117
Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012, ApJL, 747, L1
Pakmor, R., Kromer, M., Taubenberger, S., & Springel, V. 2013, ApJL, 770, L8
Pan, Y.-C. 2020, ApJL, 895, L5
Papish, O., Soker, N., García-Berro, E., & Aznar-Siguán, G. 2015, MNRAS, 449, 942
Patat, F., Chandra, P., Chevalier, R., et al. 2007, Sci, 317, 924
Patra, K. C., Yang, Y., Brink, T. G., et al. 2021, arXiv:2110.07980
Perets, H. B., Zenati, Y., Toonen, S., & Bobrick, A. 2019, arXiv:1910.07532
Piersanti, L., Gagliardi, S., Iben, I., Jr., & Tornambé, A. 2003, ApJ, 583, 885
Raskin, C., Timmes, F. X., Scannapieco, E., Diehl, S., & Fryer, C. 2009, MNRAS, 399, L156
Rosswog, S., Kasen, D., Guillochon, J., & Ramirez-Ruiz, E. 2009, ApJL, 705, L128
Ruiter, A. J. 2020, IAUS, 357, 1
Ruiz-Lapuente, P. 2019, NewAR, 85, 101523
Sankrit, R., Raymond, J. C., Blair, W. P., et al. 2016, ApJ, 817, 36
Santander-García, M., Jones, D., Alcolea, J., Bujarrabal, V., & Wesson, R. 2021, arXiv:2110.15261
Schweizer, F., & Lasker, B. M. 1978, ApJ, 226, 167
Sharma, Y., Fremling, C., Sollerman, J., et al. 2021, in Work Presented in the SuperVirtual 2021 Meeting, Poster 39
Shen, K. J., Kasen, D., Miles, B. J., & Townsley, D. M. 2018, ApJ, 854, 52
Smith, M., Nichol, R. C., Dilday, B., et al. 2012, ApJ, 755, 61
Soker, N. 2015, MNRAS, 450, 1333
Soker, N. 2018, SCPMA, 61, 49502
Soker, N. 2019a, NewAR, 87, 101535
Soker, N. 2019b, MNRAS, 490, 2430
Soker, N., García-Berro, E., & Althaus, L. G. 2014, MNRAS, 437, L66
Soker, N., Kashi, A., García-Berro, E., Torres, S., & Camacho, J. 2013, MNRAS, 431, 1541
Sternberg, A., Gal-Yam, A., Simon, J. D., et al. 2011, Sci, 333, 856
Szalai, T., Zsíros, S., Fox, O. D., et al. 2019, ApJS, 241, 38
Tanikawa, A., Nakasato, N., Sato, Y., et al. 2015, ApJ, 807, 40
Tanikawa, A., Nomoto, K., & Nakasato, N. 2018, ApJ, 868, 90
Tanikawa, A., Nomoto, K., Nakasato, N., & Maeda, K. 2019, ApJ, 885, 103
Toonen, S., Perets, H. B., & Hamers, A. S. 2018, A&A, 610, A22
Tsebrenko, D., & Soker, N. 2015, MNRAS, 447, 2568
Tucker, M. A., Shappee, B. J., Kochanek, C. S., et al. 2021, arXiv:2111.01144
van Kerkwijk, M. H., Chang, P., & Justham, S. 2010, ApJL, 722, L157
van Rossum, D. R., Kashyap, R., Fisher, R., et al. 2016, ApJ, 827, 128
Volk, K., & Kwok, S. 1985, A&A, 153, 79
Wang, B. 2018, RAA, 18, 049
Wang, B., Meng, X., Chen, X., & Han, Z. 2009, MNRAS, 395, 847
Webbink, R. F. 1984, ApJ, 277, 355
Whelan, J., & Iben, I., Jr. 1973, ApJ, 186, 1007
Williams, B. J., Blair, W. P., Borkowski, K. J., et al. 2018, ApJ, 865, L13
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2014, ApJ, 790, 139
Wiseman, P., Sullivan, M., Smith, M., et al. 2021, MNRAS, 506, 3330
Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371
Wu, C., Wang, B., Wang, X., Maeda, K., & Mazzali, P. 2020, MNRAS, 495, 1445
Yungelson, L. R., & Kuranov, A. G. 2017, MNRAS, 464, 1607
Zenati, Y., Toonen, S., & Perets, H. B. 2019, MNRAS, 482, 1135
Zeng, X., Wang, X., Esamdin, A., et al. 2021, ApJ, 919, 49