Supernovae Ia in 2019 (review): a rising demand for spherical explosions

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ABSTRACT

I review new studies of type Ia supernovae (SNe Ia) from 2019, and use these to improve the comparison between the five binary SN Ia scenarios. New low polarisation measurements solidify the claim that most SN Ia explosions are globally spherically symmetric (clumps are possible). Explosions by dynamical processes, like explosions that take place during a merger process of two white dwarfs (WDs) in the double degenerate (DD) scenario, or during an accretion process in the double detonation (DDet) scenario and in the single degenerate (SD) scenario, lead to non-spherical explosions, in contradiction with observations of normal SNe Ia. I argue that these (DD, DDet, SD) scenarios account mainly for peculiar SNe Ia. The explosion of a Chandrasekhar mass ($M_{\text{CH}}$) WD (deflagration to detonation process) has a global spherical structure that is compatible with observations. To reach spherical explosions, SN Ia scenarios should allow for a time delay between the formation of an $M_{\text{CH}}$-WD and its explosion. As such, I split the DD scenario to a channel without merger explosion delay (MED) time (that forms mainly peculiar SNe Ia), and a channel with a MED, the DD-MED channel (scenario). I speculate that the main contributors to normal SNe Ia are the core degenerate (CD) scenario, the DD-MED scenario, both have $M_{\text{CH}}$ spherical explosions, and the DD scenario that has sub-$C_{\text{CH}}$ non-spherical explosions.

Keywords: supernovae: general; binaries: close; white dwarfs; Astrophysics - Solar and Stellar Astrophysics; Astrophysics - High Energy Astrophysical Phenomena

1. INTRODUCTION

The year 2019 saw the continuation of the debate between the supporters of the five binary scenarios for type Ia supernovae (SNe Ia; in Soker 2019 I justify this partition to five scenarios). Despite several scientific meetings and tens of papers (e.g., Liu, & Stancliffe 2018; Ablimit, & Maeda 2019b; Ashall et al. 2019b; Bravo et al. 2019; Brown et al. 2019; Calder et al. 2019; Chakradhari et al. 2019; Chen et al. 2019b; Di Stefano 2019; Graur 2019; Graur et al. 2019; Heringer et al. 2019b; Konyves-Toth et al. 2019; Leung, & Nomoto 2019; Liu et al. 2019; Miles et al. 2019; Moriya et al. 2019; Pan et al. 2019; Siebert et al. 2019; Taubenberger et al. 2019; Wu et al. 2019; Han et al. 2020; Meng 2019; Shingles et al. 2019), the community did not come closer to a consensus. A prominent example is the existence of studies that argue for Chandrasekhar SN Ia explosion alongside studies that argue for sub-Chandrasekhar SNe Ia, and studies that argue for both (e.g., Levanon, & Soker 2019b; Sarbadhicary et al. 2019; Seitenzahl et al. 2019). However, I do find some significant results in studies from 2019 that constrain some scenarios and some channels within scenarios. Since there are several reviews of SNe Ia from the years 2018-2019 (Livio & Mazzali 2018; Wang 2018b; Soker 2018; Jha et al. 2019; Ruiz-Lapuente 2019; older reviews include, e.g., Maoz et al. 2014 and Maeda, & Terada 2016, and a summary of several evolutionary routes to SNe Ia Tutukov, & Fedorova 2007) that together cover all relevant aspects of SNe Ia, in the present study I concentrate on the new results from the year 2019. I discuss only scenarios that involve binary stellar systems, and will not touch single star scenarios (e.g., Clavelli 2019).

In an earlier review (Soker 2018) I summarised the five binary SN Ia scenarios in a table, which I find to be the most convenient presentation for this review as well. I bring an updated version of that table in Table 1, and I will refer to this table throughout the review.
One can characterise the scenarios by the the following properties. (1) Number of stars at explosion, \( N_{\text{exp}} \), 1 or 2. (2) Whether a companion survives the explosion, \( (N_{\text{sur}} = 0 \) or 1). (3) Whether the mass of the exploding WD(s) at explosion is around the Chandrasekhar mass limit, \( M_{\text{Ch}} \), or whether it is sub-\( M_{\text{Ch}} \). To these we can add the partition to channels that have a merger (or accretion) to explosion delay time (MED; Soker 2018), and those that do not. Specifically, in systems that have MED a merger event or an accretion process bring the WD to a mass of close to \( M_{\text{Ch}} \), and the explosion occurs a time \( t_{\text{MED}} \) after the WD has reached the mass \( M_{\text{WD}} \approx M_{\text{Ch}} \), where \( t_{\text{MED}} \) is much larger than the dynamical time.

- The core degenerate (CD) scenario has \([N_{\text{exp}}, N_{\text{sur}}, M]\)\(_{\text{CD}} = [1, 0, M_{\text{Ch}}] \). In this scenario there is always a delay from merger to explosion (MED).

- The double degenerate (DD) scenario has \([N_{\text{exp}}, N_{\text{sur}}, M]\)\(_{\text{DD}} = [2, 0, \text{sub}-M_{\text{Ch}}] \) when explosion occurs during or shortly after merger. However, if there is a long MED, which is actually the classical DD scenario, then the explosion has \([N_{\text{exp}}, N_{\text{sur}}, M]\)\(_{\text{DD,MED}} = [1, 0, M_{\text{Ch}}] \). These numbers are as in the CD scenario. The difference between the CD scenario and the DD-MED scenario is that in the DD-MED scenario there is a delay time from the formation of the two WDs to merger that is determined by gravitational waves, while in the CD scenario the merger occurs during the common envelope evolution (CEE) phase, and so gravitational waves play no role. A big challenge to the DD-MED scenario is that in many cases the merger of two CO WDs does not lead to a SNe Ia with a MED (e.g., Wu et al. 2019). The double detonation (DDet) scenario has \([N_{\text{exp}}, N_{\text{sur}}, M]\)\(_{\text{DDet}} = [2, 1, \text{sub}-M_{\text{Ch}}] \). This scenario does not allow for any MED. Shortly after the transfer of helium from the companion onto the WD starts, explosion takes place.

- The Single degenerate scenario has \([N_{\text{exp}}, N_{\text{sur}}, M]\)\(_{\text{SD,MED}} = [2, 1, M_{\text{Ch}}] \). The non-detection of the expected companions inside supernova remnants (SNRs; e.g., Li, C. et al. 2019; but I note that Abilimit, & Maeda 2019a argue that it will be hard to detect the companion for a magnetic WD), the general no detection of hydrogen (e.g., Holmbo et al. 2019), or the very low mass of hydrogen even when rare observations do show hydrogen (e.g., Kollmeier et al. 2019; Prieto et al. 2019), suggest that for normal SNe Ia all cases must have a MED, what originally was termed spin-up/spin-down evolution as rotation keeps the WD from exploding until it loses angular momentum (e.g., Piersanti et al. 2003; Di Stefano et al. 2011; Justham 2011; Boshkayev et al. 2014; Wang et al. 2014; Benvenuto et al. 2015). Meng, & Li (2019) suggest that the common-envelope wind channel of the SD-MED scenario (Meng, & Podsiadlowski 2017), can leave a surviving sdB companion which is hard to detect. They further estimate that SNe Ia with an sdB companion might contribute 22% of all SNe Ia. In the present study I refer to the SD-MED channel when referring to normal SNe Ia, and to the SD scenario without MED when referring to peculiar SNe Ia, unless stated otherwise.

- The WD-WD collision (WWC) scenario has \([N_{\text{exp}}, N_{\text{sur}}, M]\)\(_{\text{WWC}} = [2, 0, \text{sub}-M_{\text{Ch}}] \). Even if the combined mass of the two WDs is larger than \( M_{\text{Ch}} \), the explosion densities are of sub-\( M_{\text{Ch}} \) explosions.

Table 1 has several significant differences from the previous comparison table (Soker 2018).

1. I removed the WWC scenario from the table because it suffers from two severe problems. The first severe problem is that it can at most account for less than one per cent of all SNe Ia, e.g., Toonen et al. (2018) who solidified similar earlier claims (later studies have reached the same qualitative conclusion, e.g., Haim, & Katz 2018; Hallakoun & Maoz 2019; Hamers & Thompson 2019). The second severe problem is that the collision of the two WDs lead to highly non-spherical explosion (e.g., Kushnir et al. 2013), contrary to both the morphologies of SNRs Ia and to the new polarisation studies of SNe Ia. I do note that there are some studies in 2019 that claim for the WWC scenario (e.g., Wygoda et al. 2019a,b), and that this scenario might account for rare types of peculiar SNe Ia. In particular, Valley et al. (2019b) find that some SNe Ia show bimodal velocity distributions of \( ^{56}\text{Ni} \) decay products, and Livneh, & Katz (2020) find evidence for asymmetrical Si distribution. These papers claim that their results support the WWC scenario for many SNe Ia. In the present review I attribute such bimodal and asymmetrical distributions to large
### Table 1. Confronting SN Ia scenarios with observations

| Scenario[^1[^2] | Core Degenerate (CD) | Double Degenerate (DD) | Double Degenerate (DD-MED) | Double Degenerate (DDet) | Single Degenerate (SD-MED) |
|----------------|----------------------|------------------------|-----------------------------|---------------------------|---------------------------|
| **Channel by MED** | MED built-in. | No MED | MED | No MED (not allowed) | MED (with no MED peculiar SNe Ia) |
| **Explosion type** | $M_{Ch}$ | sub-$M_{Ch}$ | $M_{Ch}$ | sub-$M_{Ch}$ | $M_{Ch}$ |
| Presence of 2 opposit Ears in some SNR Ia[^3] | Explained by the SN inside planetary nebula (SNIP) mechanism. | Low mass Ears if jets during merger (Tsebrenko & Soker 2013). | Requires a short gravitational waves delay time shortly after CEE; unlikely. | No Ears are expected for He WD companion. | OP[^4] Ears by jets from accreting WD (Tsebrenko & Soker 2013). |
| Spherical SNRs + low polarisations | Expected in all cases. | Cannot explain. | Expected in all cases. | Cannot explain. | Explained in most cases (with MED). |
| $\approx 1M_{\odot}$ CSM in Kepler’s SNR | The massive CSM shell might be a PN. | No CSM shell | Requires a short gravitational waves delay time shortly after CEE; unlikely. | Any CSM is of a much lower mass. | OP[^5] Can be explained by heavy mass loss from an AGB donor. |
| The need to synthesi s $^{56}$Mn and other elements. | $M_{Ch}$ can do it | Not possible | $M_{Ch}$ can do it | Not possible | $M_{Ch}$ can do it |
| **Main Scenario Predictions** | 1. Single WD exploded. | 1. Single WD exploded. | 1. A companion survives. | 1. A companion survives. | 1. A companion survives. |
| 2. Massive CSM in some cases (SNIP). | 2. Many explosions with $M_{WD} \sim M_{Ch}$. | 2. Many explosions with $M_{WD} \sim M_{Ch}$. | 2. Asymmetrical explosion | 2. Many explosions with $M_{WD} \sim M_{Ch}$. | 2. Asymmetrical explosion |
| 3. $M_{WD} \geq M_{Ch}$ | 3. Spherical explosions | 3. Spherical explosions | 3. $M_{WD} < 1.2M_{\odot}$ | 3. $M_{WD} < 1.2M_{\odot}$ | 3. $M_{WD} < 1.2M_{\odot}$ |
| **General Strong Characteristics** | 1. Explains some SN Ia with H-CSM. | 1. Explains very well the delay time distribution (DTD). | Explains very well the delay time distribution (DTD). | Ignition easily achieved | 1. Accreting massive WDs exist. |
| 2. Spherical explosions | 2. Ignition process | 2. Ignition process | 2. Many explosions with $M_{WD} \geq M_{Ch}$. | 1. To explain the non-detection of helium. | 2. To explain the DTD and number of SNe Ia. |
| 3. Many explosions with $M_{WD} \geq M_{Ch}$. | 3. To solidify the claim for $M_{Ch}$ WDs (Bear, & Soker 2018). | 3. To solidify the claim for $M_{Ch}$ WDs (Bear, & Soker 2018). | 3. Spherical explosions | 2. To find surviving companions | 3. To find surviving companions |
| 4. $M_{Ch}$ | 4. DTD | 4. DTD | 4. $M_{Ch}$ | 4. DTD | 4. $M_{Ch}$ |
| **Work for future studies** | 1. Ignition process | 1. Ignition process | 1. To derive spherical explosions | 1. To explain the non-detection of helium. | 1. Ignition process |
| 2. To derive spherical explosions | 2. Merge process | 2. Merge process | 2. To explain the non-detection of helium. | 2. To explain the DTD and number of SNe Ia. | 2. To explain the DTD and number of SNe Ia. |
| 3. To solidify the claim for $M_{Ch}$ WDs (Bear, & Soker 2018). | 3. To solidify the claim for $M_{Ch}$ WDs (Bear, & Soker 2018). | 3. To solidify the claim for $M_{Ch}$ WDs (Bear, & Soker 2018). | 3. To solidify the claim for $M_{Ch}$ WDs (Bear, & Soker 2018). | 3. To find surviving companions | 3. To find surviving companions |
| **Contribution to normal SNe Ia[^5]** | $\approx 20 - 50\%$ | $\approx 20 - 40\%$ | $\approx 20 - 40\%$ | $\approx 0 - 10\%$ | $\approx 0 - 10\%$ |
| **Contribution to peculiar SNe Ia[^5][^6]** | $\approx 0 - 10\%$ | $\approx 30 - 70\%$ | $\approx 0 - 10\%$ | $\approx 10 - 30\%$ | $\approx 20 - 50\%$ by the SD scenario without MED |

**Notes:**

[^1]: Scenarios for SN Ia by alphabetical order, not including the WWC scenario; see Soker (2018) for an early version of this table that does include the WWC scenario, but does not include the DD-MED channel.

[^2]: The first three rows are the names, and explosion types: Chandrasekhar mass explosion, $M_{Ch}$, or sub-Chandrasekhar mass explosion, sub-$M_{Ch}$.

[^3]: The observations in rows 4-10 refer to normal SNe Ia.

[^4]: OP (only peculiar) means that the SD scenario without MED can explain this observation, but not the SD-MED scenario. Therefore, explanation of the particular observation is possible within the SD channels only for peculiar SNe Ia.

[^5]: Last two rows present my very crude estimates of the contribution of each channel to normal and peculiar SNe Ia, respectively.

[^6]: Despite that the WWC scenario is not in the present table, I do include it in the list of SN Ia and peculiar SN Ia scenarios. I estimate that it might contribute up to a few percents of peculiar SNe Ia.

[^56]: Ni and Si clumps in the explosion mechanism, although the global explosion in normal SNe Ia is spherical. These papers and others, show that we still should consider the WWC scenario. In this review I do not include it in the comparison table because my aim is to list the contribution of each scenario, and there are studies that solidify the claim that the WWC scenario does not contribute more than one percent of SNe Ia and peculiar SNe Ia (e.g., Toonen et al. 2018).

2. In my previous review (Soker 2018) I used the comparison of the five scenarios with each other and with observations to argue that scenarios must allow, at least in some cases, for a time delay between the dynamical process of merger or the dynamical process of mass accretion to explosion.
This merger to explosion delay (MED) was the main conclusion then. In the present study I incorporate the MED as a property that splits scenarios to different channels (second row in Table 1).

3. I consider the SD scenario without MED not to be able to explain normal SNe Ia. For example, Knutttila et al. (2019) and Graur, & Woods (2019) strengthen earlier claims that rule out hot and luminous progenitors as expected in some channels of the SD scenario. Their arguments do not apply to the SD-MED scenario (spin-up/spin-down) that in principle might account for a fraction of normal SNe Ia. For that, I removed the two problems of no detection of a surviving companion and no hydrogen in the ejecta from being severe difficulties of the SD scenario. However, a companion should still survive even if a faint one, and in some cases we should expect hydrogen.

4. The outcomes of the DD scenario when explosion occurs within several dynamical time scales after merger or at much later times (the DD-MED) are very different. For that, I find it necessary to split this scenario to two columns in Table 1. A MED might take place when the merger remnant has a mass of $M_{\text{rem}} \simeq M_{\text{CH}}$.

5. I changed somewhat the rows. For example, to emphasise the new polarisation studies that suggest spherical explosions, I added the fifth row.

6. Following the above changes and new results from 2019, I changed my estimates of the contribution of each channel to normal and peculiar SNe Ia.

The above discussion of all five scenarios underlines the importance to consider all scenarios. This is also evident from new observations in 2019. One example is of SNe Ia that interact with a circumstellar matter (CSM), so called SNe Ia-CSM. In their new study Graham et al. (2019) estimate that SNe Ia-CSM amount to $f_{\text{CSM}} < 0.06$ of all SNe Ia (I discuss the implications of this important study in section 5). In that respect it is mandatory to realise that not only the SD scenario, but also the CD scenario, can account for SNe Ia-CSM (Soker 2019). In section 3 I discuss another example of the need to consider more than one scenario.

I turn to discuss some new studies from 2018/2019 and their implications to the different scenarios. These new studies join older studies (that I do not review here) in challenging one or more scenarios. When comparing theoretical studies to observations these challenges cannot be ignored. There is no scenario that is free from challenges, some that I find hard, or even impossible, to overcome. For example, I do not see how the WWC scenario overcome the two challenges I mentioned in point (1) above, and for that I do not list it in Table 1.

I note again that I cite mainly papers from 2019, although in most cases there are earlier relevant papers, because this review is about studies from 2019 (and to some extend from 2018) and their new implications.

**Summary of section 1.** It is mandatory to consider all scenarios when comparing observations to theory. There are five (5; not 2) scenarios, with some of them having multiple channels. Most significant splitting to channels is that to the two channels of the DD scenario according to the presence (the DD-MED channel) or not of a MED (merger to explosion delay) time. I find the observation that most normal SNe Ia have globally spherical explosions to be one of the most significant in 2019. This finding, alongside others observations, strongly limit the contribution of the DDet scenario, the SD scenario without MED, and the DD scenario without MED to normal SNe Ia.

2. SPHERICALLY SYMMETRIC EXPLOSIONS

2.1. New polarisation observations

I consider the observations of very low polarisation of SNe Ia (Cikota et al. 2019; Yang et al. 2019) to be the most significant type of observations published in 2019. These observations suggest that most SNe Ia have spherical explosions. The globally spherical morphologies of many SNRs Ia (but not all are spherical, e.g., Alsaberi et al. 2019) also suggest that most SNe Ia have spherical explosions (review by Soker 2018), but the new observations put this conclusion on the forefront (for a summary of polarisation of SNe Ia see, e.g., Meng et al. 2017). I note that Fang et al. (2019) show that they can reproduce the departure of the SNR of SN 1006 from spherical morphology by an interaction of a spherical explosion with an ambient medium with a density discontinuity. As well, Luken et al. (2020) conclude that the young type Ia (Borkowski et al. 2013) SNR G1.9+0.3 that has an asymmetrical structure expands into an inhomogeneous interstellar medium (ISM).

Cikota et al. (2019) study the polarisation of 35 SNe Ia, and argue that their results support the possibility of two distinct explosion mechanisms. Their analysis shows the peak polarisation of the Si II line to be consistent with the expectation of the DDet scenario and of the delayed-detonation mechanism of $M_{\text{ch}}$ explosions. The violent merger of the DD scenario predicts (e.g., Bulla et al. 2016a) too high polarisation (e.g., for 34 out of 35 SNe Ia).
Yang et al. (2019) note that their detection of low polarisation in the normal SN Ia SN 2018gv implies a high degree of spherically symmetric explosion, and that this in turn is consistent with the expected morphology of the delayed detonations explosion mechanism and is inconsistent with the merger-induced explosion mechanism.

For the benefit of the discussion in section 5, I recall that not all SNe Ia have low polarisation. Cikota et al. (2017) find that the polarisation curves of some SNe Ia sight-lines are similar to those of some proto-planetary nebulae (PNe). They claim that this suggests that some SNe Ia explode inside the wind of a post-asymptotic giant branch star. The case of a SN Ia that explodes inside a proto-PN or a PN is termed SNIP (Tsebrenko & Soker 2015a), for a SN inside a PN (Dickel & Jones 1985).

The findings that most SNe Ia have global spherically symmetric explosions strongly challenges several explosion mechanisms. Ferrand et al. (2019) show in a recent paper that morphological signatures of the explosion can still be detected hundreds of years after explosion, so that an interaction with the ISM cannot erase global asymmetries of SN Ia explosions.

I here discuss only two recent papers on explosion mechanisms. But I do note that alongside a global spherical structure of the SN Ia ejecta, the ejecta might be clumpy (e.g., Millard et al. 2019; Sato et al. 2019), particularly the iron group elements (e.g., Maguire et al. 2018).

2.2. The DDet scenario

I consider first the DDet scenario. This scenario has some strong points, e.g., Townsley et al. (2019) perform hydrodynamical simulations of the DDet scenario and find that it can account for the brightness and spectra of SNe Ia (see also, e.g., Polin et al. 2019a). However, the observations that suggest spherical SN Ia explosions strongly challenge this scenario. However, I do note that Bulla et al. (2016b) calculate the polarisation of the DDet scenario and find it to be low enough to be compatible with observations.

The first process that leads to a non-spherical explosion is the collision of the ejecta with the surviving companion. This collision forms a conical region behind the companion where the density is very low (e.g., Tanikawa et al. 2018, 2019; Bauer et al. 2019). But there is another process that causes deviation from spherical explosion.

Consider the “dynamically driven double-degenerate double-detonation” (D^6) scenario that Shen et al. (2018) suggest as an explanation to the three hyper-velocity WDs that they identify with Gaia (see simulation by Tanikawa et al. (2019)). Each of this three WDs is the companion that survived a DDet SN Ia. Neunteufel et al. (2019) find that the parameter space of the DDet scenario with a non-degenerate helium donor might account for no more that 3% of all SNe Ia. In the D^6 model, though, the helium-donor is a WD.

According to Shen et al. (2018), the respective velocities of the three hypervelocity WDs relative to the Galaxy are \( v_2 \approx 1300 \, \text{km s}^{-1} \), \( 2300 \, \text{km s}^{-1} \), and \( 2400 \, \text{km s}^{-1} \), with large uncertainties. In the DDet scenario these velocities are the pre-explosion orbital velocities of the respective helium-donor WD companion in each system. To achieve a high velocity of \( v_2 \approx 2000 \, \text{km s}^{-1} \) the mass of the WD companion is \( M_2 \approx 1M_{\odot} \) (Shen et al. 2018). Since the exploding WD has a similar mass, the orbital velocity of the exploding WD is \( v_{1, \text{orb}} \approx v_2 \approx 2500 \, \text{km s}^{-1} \) in the two cases above with high hypervelocities. What causes departure from spherical explosion is that during the explosion the companion and the ejecta do not move on straight lines, but rather continue to curve in the sense of their original orbital motion. This implies that the direction of ejection of the center of mass of low-velocity ejecta is not as that of higher velocity ejecta. Let us demonstrate this qualitatively.

Consider then the explosion process of the WD in the presence of a helium-donor star of similar mass. For a demonstrative case I take the spherical density profiles from Dwarkadas & Chevalier (1998)

\[
\rho_0(v, t) = \frac{M_e}{8\pi v_e t} e^{-v/v_e}, \quad v_e = \left( \frac{E_k}{6M_e} \right)^{1/2},
\]

where \( M_e \) and \( E_k \) are the total ejecta mass and kinetic energy, respectively. For \( M_e = 1M_{\odot} \) and \( E_k = 10^{51} \, \text{erg} \) we find \( v_e = 2895 \, \text{km s}^{-1} \). Integration over the volume shows that half of the ejecta mass is within a velocities of \( v_h = 7750 \, \text{km s}^{-1} \) \( \approx 3.4v_{1, \text{orb}} \), and quarter of the mass within a velocity of \( v_q = 5000 \, \text{km s}^{-1} \).

By the time the coordinate of half the mass expands from \( v_h \) to \( v_q \) we find that for quarter of the mass \( v_e = 2895 \, \text{km s}^{-1} \) and \( \alpha_q = 53^\circ \). There is a need for more accurate calculations to calculate the polarisation days after explosion, and to re-
veal the later SNR morphology. But this simple calculation shows that the D\textsuperscript{6} scenario with a companion that escapes the system after explosion with \(v_2 \gtrsim 2000\) km s\(^{-1}\) has highly non-spherical explosion, contrary to observations.

In the case of \(v_2 \simeq 1300\) km s\(^{-1}\) the mass of the hypervelocity WD is \(M_2 \approx 0.2M_\odot\), and the orbital velocity of the WD that exploded was \(v_{1,\text{orb}} \simeq 300\) km s\(^{-1}\). In that case the orbital motion has a minor influence on the explosion morphology, which will nonetheless be non-spherical due to the collision of the ejecta with the companion.

The production of a non-spherical SNe Ia is not the only recent problem of the DDet scenario. Polin et al. (2019b) show that although the DDet scenario can qualitatively reproduce sub-luminous SNe Ia spectra in the nebular phase, these explosions produce too much [CaII] emission compared to most normal SNe Ia.

Another general problem is that sub-\(M_{\text{Ch}}\) explosions cannot yield some isotopes (e.g., Bravo 2019), such as \(^{55}\text{Mn}\) (seventh row in Table 1).

2.3. The hybrid HeCO channel of the DD scenario

The second study I consider deals with the hybrid HeCO channel of the DD scenario (Zenati et al. 2019; Perets et al. 2020). (The HeCO hybrid channel of the DD scenario is different than the hybrid CONe channel of \(M_{\text{Ch}}\) deflagration to detonation explosions, e.g., Augustine et al. 2019). Perets et al. (2020) simulate the destruction of a HeCO WD by a CO WD with 2D hydrodynamical simulations that include nuclear reactions. Perets et al. (2020) set their initial conditions to have a HeCO torus around the CO WD. They obtain a double detonation process and ignite both the CO WD and the HeCO torus. They can account for several important properties of SNe Ia, like the light curves, spectra, and the range of peak-luminosities. They further argue that together with the contribution from the DD scenario of two massive CO WDs they can reproduce the rate and delay-time distribution of SNe Ia.

However, they face several challenges. Their 2D code forces them to simulate axisymmetrical flow. For that, they could not actually follow the destruction of the HeCO WD and establish whether the destructed HeCO WD forms a torus before ignition. The second challenge is the high density along the symmetry axis inside the CO WD that they obtain in their simulations. Their 2D axisymmetrical numerical grid necessarily forces the shock wave that the ignition of the HeCO torus induces in the CO WD to converge on the axis. Namely, their 2D grid ignites a ring around the symmetry axis, rather than a point in reality. In reality, the ignition that starts

in one point will not lead to an axisymmetrical shock wave, and it is not clear whether they can obtain high enough densities inside the CO WD. I also note that even with these high densities (which might be overestimated) they do not synthesis some elements, such as \(^{55}\text{Mn}\).

I consider the third challenge to be the strongest one. They present their numerical grid up to a distance of \(6 \times 10^9\) cm from the center of the flow. From what they present, one sees that the explosion is highly non-spherical. There is a fast polar outflow and much slower equatorial ejecta. It is a challenge for the hybrid HeCO channel of the DD scenario to show they can account for the new low polarisation measurements, and for globally spherical SNRs Ia.

★ Summary of section 2. The new polarisation studies from 2019 (Cikota et al. 2019; Yang et al. 2019) impose firm constraints on explosion mechanisms to yield explosions that are globally spherical, at least in most cases, if not in all normal SNe Ia. (Small features, such as ‘Ears’ are possible; Table 1.) Interestingly, interactions that seem more easily to explode in numerical simulations have highly non-spherical ejecta. These include the violent merger of the DD scenario, the WWC scenario, possibly the D\textsuperscript{6} channel of the DDet scenario, and the newly simulated hybrid HeCO channel of the DD scenario, as I discussed above. The deflagration-to-detonation explosion mechanism of \(M_{\text{Ch}}\) WDs lead to spherical explosions, and so I favour this explosion mechanism. Although there is a need to work out several steps in this explosion mechanism, the new study by Poludnenko et al. (2019) strongly supports the case for the deflagration-to-detonation explosion mechanism.

3. EARLY EXCESS EMISSION

An interesting class of SNe Ia is that of SNe Ia that show early (\(\lesssim 5\) days) excess emission in their light curve (e.g., Jiang et al. 2018; Li, W. et al. 2019; Shappee et al. 2019; Dimitriadis et al. 2019a). The SD scenario predict this kind of early emission in most SNe Ia (e.g., Kasen 2010), unless there is a very long MED during which the mass-donor radius decrease by an order of magnitude or more, i.e., a giant donor that becomes a WD. My point here is that such an emission is possible also in the DD scenario if the explosion takes place within a time of about \(10^3 \lesssim t_{\text{MED}} \lesssim 1\) day, as the ejecta collides with disk-originated matter (DOM; Levanon, & Soker 2019a).

The positive side for the DD scenario of the requirement of \(t_{\text{MED}} \gtrsim 10^3\) s \(\gg t_{\text{dyn}}\), where \(t_{\text{dyn}} \simeq 10\) s is the dynamical time of the merger process, is that the merger product has time to acquire spherical structure
that will lead to the required spherical explosion (section 2.1). The rarity of the early excess emission might suggest that in most cases the MED of the DD scenario is longer than tens of years to allow the DOM to disperse (Levanon et al. 2015), again, leading to spherical explosion.

The finding that early excess emission is rare (e.g., Fausnaugh et al. 2019), and the non-detection of hydrogen in the ejecta (e.g., Dimitriadis et al. 2019b), or only a very low mass of hydrogen in the ejecta (section 4), imply that if the SD scenario accounts for some SNe Ia, there must be a very long MED. Namely, it must be the SD-MED scenario.

**Summary of section 3.** Early excess emission can occur in principle both in the SD and in the DD scenarios. The new findings of early excess emission and their rarity suggest that in both scenarios the common channel is the one where there is a merger (or accretion) to explosion delay (MED) time. Namely, for normal SNe Ia the DD-MED and SD-MED scenarios dominate the DD and the SD scenarios, respectively.

4. HYDROGEN IN SNE Ia

Most recent studies find no hydrogen in SNe Ia (e.g., Tucker et al. 2019). This by itself almost rules-out the SD scenario without MED (e.g., Dimitriadis et al. 2019b, or only a very low mass of hydrogen in the ejecta (section 4)), and the non-detection of hydrogen in rare cases (section 4). However, Heringer et al. (2019) estimate the hydrogen mass in rare cases to be

$M_H \approx 10^{-3}M_\odot \text{ in rare cases, rules out the SD scenario that has no long MED (} t_{\text{MED}} \gtrsim 10^7 \text{ yr; }$ Soker 2018). The very low hydrogen mass in rare cases might come from a planet that the SN Ia evaporates.

The time $t_{\text{SF-E}}$ can be composed from several times. For scenarios that involve two WDs there are in principle 3 times. These are the time from star formation to explosion, $t_{\text{SF}}$, the time for gravitational waves to merge the two WDs, $t_{\text{GW}}$, and the time from the merger of the two WDs to explosion, the MED time $t_{\text{MED}}$. Namely, $t_{\text{SF-E}}(\text{DD}) = t_{\text{SF-CE}} + t_{\text{CEED}} = t_{\text{SF-CE}} + t_{\text{GW}} + t_{\text{MED}}$.

There are some SNe Ia that occur while there is a CSM around the explosion cite, so called SNe-CSM. Graham et al. (2019) estimate the fraction of SNe Ia-CSM with close CSM to be $f_{\text{CSM}} < 0.06$ of all SNe Ia. In addition, there are cases with CSM further away. Over all, the presence of a CSM implies that in scenarios that involve a CEE the explosion occurs within a short time after the CE, $t_{\text{CEED}} \lesssim 10^6 \text{ yr}$.

I used the new findings of Graham et al. (2019) and of Friedmann & Maoz (2018) and Heringer et al. (2019a),
to study the relation of SNe Ia that occur at short times (within a million years) after the CEE, and those that take place long after the CEE. My conclusion (Soker 2019) is that the population of SNe Ia with \( t_{\text{CEED}} \lesssim 10^6 \text{yr} \) amounts to \( \approx \times 0.1 \) of all SNe Ia. I further concluded that the expression for the rate of these SNe Ia is different from that of the DTD billions of years after star formation (equation 2).

From these conclusions I suggested that the physical processes that determine the explosion time shortly after the CEE are different (at least to some extend) than the processes that determine the explosion times long after the CEE. I here argue that at least those that occur within a million years after the CEE come from the CD scenario. I do note thought that there are claims that the CD scenario contributes less than my estimate in the Table 1 (e.g., Wang et al. 2017).

\textbf{Summary of section 5.} New results from 2018-2019 strengthen the case for a population of SNe Ia that occur within a million years after the CEE of their progenitors. The other population is of SNe Ia that occur much later, over a timescale of \( \approx 10^7 \text{yr} \) and longer. The processes that determine the delay time from the CEE to explosion are different (at least somewhat) in these two populations. I suggest that the short-delay population comes mainly from the CD scenario.

6. PECULIAR SNE Ia

Peculiar SNe Ia include SNe Iax, Ca-rich transients, SN 2002es-like SNe Ia, SN 1991bg-like SNe Ia, 2009dc-like SNe Ia-pec, and more (e.g., review by Jha et al. 2019). Chen et al. (2019a) study a luminous SNe Ia, and suggest to replace the name “Super-Chandrasekhar SN Ia” by “2009dc-like SN Ia-pec”, that I use here. In Table 1 I list my crude estimate of the contribution of different scenarios to peculiar SNe Ia. (Maeda, & Terada 2016 present a different type of table of some scenarios and their properties in relation to normal and peculiar SNe Ia but that table does not include the CD scenario nor estimates of the fractional contribution of each scenario.)

In the summary of section 2 I note that dynamical binary interactions that numerical simulations show to ignite one or both WDs (e.g., the violent merger, the D⁶, the hybrid HeCO channels of the DD scenario, and the WWC scenario), have highly non-spherical explosions. Although some studies show that the ignition in the DDet scenario might not be easy (e.g., Wu, & Wang 2019), I assume that ignition does take place but lead to highly asymmetrical explosions (section 2.2). For that, I find that these scenarios and channels are unlikely to account for a large fraction of normal SNe Ia. However, they might explain a large fraction of peculiar SNe Ia and other transients (e.g., like accretion-induced collapse, e.g., Wang 2018a), and the easy ignition in these processes suggests that peculiar SNe Ia (and similar transients) are very common, possibly even more common that normal SNe Ia. Not surprisingly, there are relatively many recent papers on peculiar SNe Ia and similar transients (e.g., Lyutikov, & Toonen 2019; Panther et al. 2019; Prentice et al. 2019).

The studies of peculiar SNe Ia from 2019 add to the growing evidence that peculiar SNe Ia come from several channels and scenarios, possibly from all scenarios listed in Table 1. Indeed, at least some peculiar SNe Ia show low polarisation as SNe Ia show (Meng et al. 2017).

The DDet scenario seems to be popular by studies of peculiar SNe Ia (e.g., Magee et al. 2019). Polin et al. (2019b) study the DDet scenario and argue that even a small amount of calcium can make a Ca-rich transient. Jacobson-Galan et al. (2019b) argue that the Ca-rich SN 2016hnk is consistent with the DDet scenario. Takaro et al. (2019) estimate the delay time from star formation to explosion of SNe Iax, and conclude that they better fit the DDet scenario than massive WR progenitors. However, other scenarios exist for these types of peculiar SNe Ia. For example, the hybrid HeCO channel of the DD scenario for Ca-rich transients (Zenati et al. 2020).

Sand et al. (2019) find no Hα emission in fast-declining SNe Ia, suggesting these do not come from the SD scenario. But not all peculiar SNe Ia are sub-\( M_{\text{Ch}} \) explosions. Galbany et al. (2019) argue that the peculiar SN 2016hnk, a Ca-strong 1991bg-like SN, comes from an \( M_{\text{Ch}} \) explosion. Jacobson-Galán et al. (2019a) spectroscopically model 44 SNe Iax. They find helium in two SNe Iax that better fit a CSM helium than a helium in the ejecta. In the majority of SNe Iax they find no helium, but still suggest that the SD scenario with helium donor might be the main contribute of SNe Iax. Meng, & Podsiedlnski (2018) propose that SNe Iax SNe Ia-CSM result from the hybrid CONe common-envelope wind channel of the SD scenario.

Raddi et al. (2019) report the observation of three runaway stars, that are chemically peculiar due to enrichment of nuclear ashes of partial oxygen and silicon burning. They deduce their masses to be in the range of \( 0.2 – 0.28 M_{\odot} \). They further speculate that these inflated WDs are the partly burnt remnants of either electron-capture supernovae or peculiar SNe Iax (e.g., Zhang et al. 2019). My view is that any thermonuclear explosion that leaves a runaway companion, e.g., simulations by Bauer et al. (2019) of the DDet (D⁶) scenario,
belongs to peculiar SNe Ia (and other transients), such as SNe Iax.

★★ Summary of section 6. The relative easy ignition of WDs by dynamical effects in numerical simulations of some scenarios and channels (e.g., accretion at a high rate or collision), as evidence also from studies from 2019, suggest that these explosions are common. However, since they are highly globally non-spherical, they cannot explain many normal SNe Ia (section 2). These non-spherical explosions, I suggest, make the majority of peculiar SNe Ia, as I summarise in Table 1. I expect, therefore, that most peculiar SNe Ia have non-spherical explosions, unlike normal SNe Ia.

7. SUMMARY

The question of the main progenitors of normal SNe Ia is unsolved yet. Not only there is no consensus on the most promising SN Ia scenario(s), but there is no consensus even on the different potential scenarios. The correct counting as of the end of 2019 is of five binary scenarios: the CD, the DD, the DDet, the SD and the WWC scenario (section 1). I list four scenarios in Table 1, where I also split the DD scenario to a channel without a merger to explosion delay (MED) time, and channel with a MED, the DD-MED channel (scenario). (It might be that we need to consider the DD channel and the DD-MED channel of the DD scenarios as two separate scenarios.) Because my estimate is that the WWC scenario contributes $\lesssim 1\%$ of both normal SNe Ia and peculiar SNe Ia, I do not include it in the Table.

According to population synthesis there are not enough double WD systems with combined mass of $M_{\text{Ch}}$ (e.g., Cheng et al. 2019; I note that Rebassa-Mansergas et al. 2019 argue that observationally it is not easy to detect WD binary systems). Therefore, the DD-MED scenario cannot account for all SNe Ia.

The strongest point of sub-$M_{\text{Ch}}$ scenarios (DD, DDet, WWC scenarios) is that they can achieve easy ignition by dynamical processes. However, they lead to highly non-spherical explosions, in contradiction with observations (Table 1). On the other hand, the main challenge of the $M_{\text{Ch}}$ scenarios (CD, DD-Med and SD scenarios) is to achieve ignition. Recent studies (e.g., Fisher et al. 2019; Poludnenko et al. 2019) show that turbulence can drive detonation (deflagration-to-detonation) in WDs, and by that turbulence increases the range of conditions for the onset of carbon detonation. This result helps the $M_{\text{Ch}}$ explosions. On the observational side, Kawabata et al. (2019) study the high-velocity SNe Ia SN 2019ein, and find its properties to be compatible with deflagration to detonation $M_{\text{Ch}}$ explosion. However, there are still open issues and observations that the $M_{\text{Ch}}$ model cannot explain (yet), e.g., Byrohl et al. (2019).

The entire set of observations brings many researchers to the conclusion that SNe Ia come both from $M_{\text{Ch}}$ explosions and from sub-$M_{\text{Ch}}$ explosions (e.g., Levanon, & Soker 2019b; Polin et al. 2019a,b; Sarbadhicary et al. 2019; Seitenzahl et al. 2019). The new study by Seitenzahl et al. (2019) which presents a new approach to study SNRs is a good example for that. By spatially resolving some nebular emission lines, they effectively perform a "tomography", i.e., they reveal the location of the reverse shock. By using evolutionary model they could constrain the type of explosion in two SNRs. They conclude that SNR 0519-69.0 was a standard $M_{\text{Ch}}$ explosion, while SNR 0509-67.5 was an energetic sub-$M_{\text{Ch}}$ explosion. As another example, Ashall et al. (2019a) support $M_{\text{Ch}}$ explosion for most SNe Ia, but note that the subluminous SN 2015bo might come from the merger of two WDs. They claim that this demonstrates the diversity of explosion scenarios of faint SNe Ia. Kobayashi et al. (2019) study galactic chemical evolution from which they conclude that sub-$M_{\text{Ch}}$ contribute up to 25% of SNe Ia in the solar neighbourhood. In dwarf spheroidal galaxies sub-$M_{\text{Ch}}$ contribute a higher fraction when star formation took place. Kirby et al. (2019) reach similar conclusions, i.e., that sub-$M_{\text{Ch}}$ explosions dominated in dwarf galaxies when they formed stars in the past. At present, $M_{\text{Ch}}$ might dominate, as they do in the Milky Way and in dwarf galaxies with extended star formation. These studies also point to both $M_{\text{Ch}}$ and sub-$M_{\text{Ch}}$ explosions.

★★ Summary of section 7. The summary of this section, and in turn of the entire review, are the last two rows of Table 1 where I list my crude estimates of the contribution of the different scenarios. This table presents my view that normal SNe Ia come both from $M_{\text{Ch}}$ explosions, mainly the CD and DD-MED scenarios, and from sub-$M_{\text{Ch}}$ explosions, mainly the DD scenario. There is a possible small contribution from the SD and DDet scenarios. Peculiar SNe Ia come mainly from the DD, DDet, and SD scenarios, all without MED.

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