The response of a helium white dwarf to an exploding type Ia supernova

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\textbf{ABSTRACT}

We conduct numerical simulations of the interacting ejecta from an exploding CO white dwarf (WD) with the He WD donor in the double-detonation scenario for Type Ia supernovae (SNe Ia), and find that the descendant supernova remnant (SNR) is highly asymmetrical, in contradiction with observations. When the donor He WD has low mass, $M_{\text{WD}} = 0.2 M_\odot$, it is at a distance of $\sim 0.08 R_\odot$ from the explosion, and helium is not ignited. The low mass He WD casts an ‘ejecta shadow’ behind it, that has imprint in the SN remnant (SNR) hundreds of years later. The outer parts of the shadowed side are fainter and its boundary with the ambient gas is somewhat flat. These features are not found in known SNRs. More massive He WD donors, $M_{\text{WD}} \approx 0.4 M_\odot$, must be closer to the CO WD to transfer mass. At a distance $a \lesssim 0.045 R_\odot$ helium is ignited and the He WD explodes. This explosion leads to a highly asymmetrical SNR and to ejection of $\sim 0.15 M_\odot$ of helium, both of which contradict observations of SNe Ia.

\textit{Subject headings:} ISM: supernova remnants — supernovae: stars: binary — binaries: close — hydrodynamics — supernovae: general

1. \textbf{INTRODUCTION}

Type Ia Supernovae (SNe Ia) are one of the most energetic events in the universe, now known to be originated by thermonuclear detonations of carbon-oxygen (CO) white dwarfs (Hoyle & Fowler\textsuperscript{[1960]}). Several possible scenarios leading to a SN Ia outburst are currently envisaged, although there might be some overlap between them. All scenarios have

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advantages and drawbacks (e.g., Tsebrenko & Soker 2014b), and there is not yet a general consensus on the leading scenario for SN Ia. In fact, it is well possible that all of them contribute to the total SN Ia rate in some unknown fraction.

These scenarios can be listed as follows, according to alphabetical order. (a) The core-degenerate (CD) scenario (e.g., Livio & Riess 2003; Kashi & Soker 2011; Soker 2011; Ilkov & Soker 2012, 2013; Soker et al. 2013; Tsebrenko & Soker 2014a). Within this scenario the WD merges with the hot core of a massive asymptotic giant branch (AGB) star. In this case the explosion might occur shortly or a long time after the merger. In a recent paper, Tsebrenko & Soker (2014b) argue that at least 20%, and likely many more, of all SNe Ia come from the CD scenario. (b) The double degenerate (DD) scenario (e.g., Webbink 1984; Iben & Tutukov 1984). This scenario is based on the merger of two WDs. However, this scenario does not specify the subsequent evolution of the merger product, namely, how long after the merger the explosion of the remnant takes place (e.g., van Kerkwijk et al. 2010). Recent papers, for example, discuss violent mergers (e.g., Lorén-Aguilar et al. 2010; Pakmor et al. 2013) as possible channels of the DD scenario, while others consider very long delays from merger to explosion, e.g., because rapid rotation keeps the structure overstable (Tornambé & Piersanti 2013). Levanon et al. (2014) argue that the delay between merger and explosion in the DD scenario should be $\gg 10$ yr. (c) The single degenerate (SD) scenario (e.g., Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004). In this scenario a white dwarf (WD) accretes mass from a non-degenerate stellar companion and explodes when its mass reaches the Chandrasekhar mass limit. (d) The double-detonation mechanism (e.g., Woosley & Weaver 1994; Livne & Arnett 1995). Here a sub-Chandrasekhar mass WD accumulates a layer of helium-rich material coming from a helium donor on its surface. The helium layer is compressed as more material is accreted and detonates, leading to a second detonation near the center of the WD (see, for instance, Shen et al. 2013 and references therein, for a recent paper). (e) The WD-WD collision scenario (e.g., Thompson 2011; Katz & Dong 2012; Kushnir et al. 2013; Aznar-Siguán et al. 2013). In this scenario either a tertiary star brings two WDs to collide, or the dynamical interaction occurs in a dense stellar system, where such interactions are likely. In some cases, the collision results in an immediate explosion. Despite some attractive features of this scenario, it can account for at most few per cent of all SNe Ia (Hamers et al. 2013; Prodan et al. 2013; Soker et al. 2014).

Finally, it should be mentioned that very recently it has been suggested that pycnonuclear reactions could be able to drive powerful detonations in single CO white dwarfs (Chiosi et al. 2014). This scenario – the so-called single WD scenario – has, however, two important shortcomings. The first one is that the typical H mass fraction found in detailed evolutionary calculations of CO WD progenitors is much smaller than that needed to ignite the core of the WD. The second drawback of this recently suggested scenario is that most SN
Ia come from WDs with masses near the Chandrasekhar limit (e.g., Seitz et al. 2013, Scalzo et al. 2014), while the mass at which ignition may possibly occur in the single WD scenario is \( \sim 1.2M_\odot \). Hence, this scenario would also only account for a small percentage of all SN Ia.

As mentioned earlier, there is some overlap between these scenarios. For example, in the violent merger model (Lorén-Aguilar et al. 2009, Pakmor et al. 2012) it is possible that during the first stages of the merger of the two CO WDs the small helium buffer (\( \sim 10^{-2}M_\odot \)) of the original CO WDs is ignited. In this case both the DD scenario and the double detonation mechanism operate simultaneously. Also, the double detonation mechanism might operate in the CD scenario.

In this paper we study the response of a donor star that is a He WD to an exploding CO WD with mass below the Chandrasekhar limit, \( M_{\text{WD}} \sim 1.0 - 1.1M_\odot \). These parameters fit the double detonation scenario where a very low mass helium shell triggers the SN Ia explosion of a CO WD (Bildsten et al. 2007, Shen & Bildsten 2009, 2014). We will answer five questions. (1) Does the shock wave induced by the ejecta ignite helium in the WD companion by adiabatic compression or by shock heating? (2) Is carbon in the ejecta ignited as it is shocked in the outer layers of the He WD? (3) Can mixing of helium from the donor and carbon from the ejecta lead to vigorous nuclear burning? (4) How much helium is entrained by the ejecta? (5) What is the morphology of the SNR long time after the explosion as the SN ejecta sweep some ambient medium gas? To do so we will adopt two masses for the He WD companion. First we study analytically and then numerically the impact of the SN Ia ejecta of a WD of mass \( 0.43M_\odot \) residing at \( \sim 0.02 - 0.03R_\odot \) from the exploding CO WD. This setting is based on the numerical simulations of Guillochon et al. (2010), Raskin et al. (2012), and Pakmor et al. (2013), for similar (but not identical) progenitors that might lead to SN Ia. In a second step, and following Bildsten et al. (2007) and Shen & Bildsten (2009) we also consider a He WD of \( 0.2M_\odot \) at an orbital separation of \( 0.08R_\odot \).

Our paper is organized as follows. In section 2 we discuss and quantify the properties of the material ejected from the disrupted CO WD, while in section 3 we assess analytically the possibility of an explosive ignition. In section 4 we conduct 2D axisymmetrical numerical simulations of the interaction of the ejecta with the He WD, and we examine nuclear reactions and helium entrainment. Finally, in section 5 we summarize our results and their implications to the double detonation scenario.
2. EJECTA PROPERTIES

To facilitate an analytical estimate we assume that the SN Ia ejecta is already in homologous expansion, and we take the profile of Dwarkadas & Chevalier (1998)

$$\rho_{SN} = A \exp(-v/v_{ejecta}) t^{-3},$$  \hfill (1)

where $v_{ejecta}$ is a constant which depends on the mass and kinetic energy of the ejecta,

$$v_{ejecta} = 2.9 \times 10^8 E_{51}^{1/2} \left(\frac{M_{SN}}{1 M_\odot}\right)^{-1/2} \text{ cm s}^{-1},$$  \hfill (2)

$E_{51}$ is the explosion energy in units of $10^{51}$ erg, and $A$ is a parameter given by

$$A = 3.3 \times 10^6 \left(\frac{M_{SN}}{1 M_\odot}\right)^{5/2} E_{51}^{-3/2} \text{ g s}^{-3} \text{ cm}^{-3}.$$  \hfill (3)

The maximum velocity of the SN Ia ejecta is $v_{SNm} \simeq 20,000 \text{ km s}^{-1}$. We use this profile both in the analytical and the numerical calculations.

For the analytical estimates derived in section 3 we now estimate the maximum ram pressure of the ejecta on the He WD. A cold He WD of mass $0.43 M_\odot$ has a radius of $\sim 0.015 R_\odot$. As it overflows its Roche lobe, with a CO WD companion of $1 M_\odot$, in a stable mass transfer the orbital separation is $\sim 3.3$ times this distance, namely, $a \simeq 0.05 R_\odot$. However, detailed numerical calculations show that for a powerful ignition to occur the mass transfer must be unstable (Guillochon et al. 2010), and the surface of the He WD that fills the Roche lobe can be as close as $\sim 0.02 R_\odot$ to the exploding CO WD (Raskin et al. 2012; Pakmor et al. 2013).

The ram pressure of the ejecta at a distance $r_e$ from the explosion at time $t$ after explosion is given by

$$P_{\text{ram}} = \rho(r_e) v^2 = A \exp(-r_e/v_{ejecta} t) t^{-5} r_e^2,$$  \hfill (4)

where $v = r_e/t$. The maximum ram pressure is achieved at time $t_{\text{max}} = r_e/(5v_{ejecta}) = 1(r_e/0.02 R_\odot) \text{ s}$, and its value is

$$P_{\text{ram}}^{\text{max}} = 5.2 \times 10^{22} E_{51} \left(\frac{r_e}{0.02 R_\odot}\right)^{-3} \text{ erg cm}^{-3}.$$  \hfill (5)

At $t = 2t_{\text{max}}$ and $t = 3t_{\text{max}}$ the pressure drops to a value of $0.38 P_{\text{ram}}^{\text{max}}$ and $0.12 P_{\text{ram}}^{\text{max}}$, respectively. The first material hits the WD at time $\sim 0.02 R_\odot/20,000 \text{ km s}^{-1} = 0.7 \text{ s} \simeq 0.7 t_{\text{max}}$, with a ram pressure of $0.7 P_{\text{ram}}^{\text{max}}$. Overall, the phase in which the pressure is larger than
\( \sim 0.3P_{\text{ram}}^{\text{max}} \) lasts for about two seconds at \( \sim 0.02R_\odot \) from the explosion. The density of the ejecta at maximum ram pressure is

\[
\rho(t_{\text{max}}) = 2.5 \times 10^4 \left( \frac{M_{\text{SN}}}{1M_\odot} \right) \left( \frac{r_e}{0.02R_\odot} \right)^{-3} \text{ g cm}^{-3}.
\]

(6)

\section{Conditions for Nuclear Ignition}

Fig. 1 shows two of the physical quantities of a 0.43\( M_\odot \) He WD which are relevant for our study, namely the pressure and density as a function of the mass coordinate \( -\log(1 - M_e/M_{\text{WD}}) \). This specific model corresponds to a WD with central temperature \( T \approx 10^7 \) K, which results in a surface luminosity \( \log(L/\odot) \sim -2.85 \), an otherwise typical luminosity of field white dwarfs, an effective temperature \( \log(T_{\text{eff}}) \approx 3.93 \), and corresponds to a sequence which was evolved performing full evolutionary calculations that consider the main energy sources and processes of chemical abundance changes during white dwarf evolution (Althaus et al. 2009). There are three possible ways in which the He WD or the CO ejecta might be ignited:

1. \textit{Shock ignition of helium.} It turns out that, for the model WD used here, He is shocked and ignited in a region where both thermal and radiation pressures play a role. In this region \( \rho \sim 10^5 \) g cm\(^{-3}\) and \( T \approx 1.2 \times 10^9 \) K. A good estimate of the temperature in the shocked region of the He WD can be obtained by equating the radiation pressure to the ram pressure given in equation (5):

\[
T_{\text{He}} \approx 1.2 \times 10^9 \left( \frac{r_e}{0.04R_\odot} \right)^{-3/4} \text{ K.}
\]

(7)

The burning time-scale of pure helium at these conditions is \( \sim 10 \) s, just a little longer than the timescale of the dynamical flow, defined as the ejecta speed divided by the He WD radius, \( \sim 0.04R_\odot/10,000 \text{ km s}^{-1} \sim 3 \) s. For these parameters, ignition conditions are reached for \( r \lesssim 0.04R_\odot \). This is compatible with the numerical results to be described in section 4.3 where the exact radius is found.

2. \textit{Carbon burning in the shocked ejecta.} The second possibility we explore is the ignition of carbon-rich material of the ejecta as it is shocked upon hitting the He WD. The post-shock pressure of the ejecta is dominated by radiation pressure. The temperature at maximum ram pressure is given by equation (7). For a distance to the explosion \( r_e = 0.02R_\odot \) we find the temperature to be \( T_{\text{CO}} \approx 2 \times 10^9 \) K. For this temperature we expect that carbon will be burned. Nevertheless, we need to compare the burning time with the dynamical timescale of the flow, \( \tau_{\text{flow}} \sim 1 \) s. For the scaling and parameters used in Sect. 2 the ejecta
density at the time of maximum ram pressure and at a distance of 0.02 $R_\odot$ from the center of explosion is $3.5 \times 10^4$ g cm$^{-3}$. If the carbon mass is half of the mass of the ejecta and the compression factor is $\sim 4$, then the post-shock density in the carbon-rich region is $\rho_C \simeq 7 \times 10^4$ g cm$^{-3} \sim 10^5$ g cm$^{-3}$. As in this scenario the companion star is much closer to the center of the explosion than the corresponding one of the single-degenerate scenario, the density of the shocked ejecta will be much higher, and the burning timescale much shorter. We find that the carbon burning timescale for this density and a typical temperature $\sim 2 \times 10^9$ K to be about one second. These temperatures and densities are achieved near the stagnation point in a small region of size $\sim 0.1r_e$ – see below. The outflow time from this region is $\sim 0.002R_\odot/1.5 \times 10^4$ km s$^{-1} = 0.1$ s. Thus, the outflow time is shorter than the burning time scale. In the numerical results to be described next we obtain no significant carbon burning, showing that the outflow time of carbon from the shocked region is indeed very short. This is unlike the case in which helium belonging to the He WD is shocked inside the He WD and cannot flow outward.

(3) Igniting helium by mixing ejecta. Even if carbon is not ignited, mixing of the ejecta at $T \sim 10^9$ K with helium might, in principle, even if helium was not ignited by the shock, power a thermonuclear runaway. In our numerical simulations we get no mixing, and this process is not important (see section 4).

For the case of a low-mass He WD we repeated all these calculations and we found that none of the previously described processes drive a powerful nuclear outburst, and thus the evolution in this case should mostly consist of a purely hydrodynamical flow. As it will be explained in detail in the next section, full hydrodynamical numerical simulations confirm this.

4. NUMERICAL SIMULATIONS

4.1. Numerical setup

We use version 4.2.2 of the FLASH gas-dynamical numerical code (Fryxell et al. 2000). The widely used FLASH code is a publicly available code for supersonic flow suitable for astrophysical applications. The simulations are done using the unsplit PPM solver of FLASH. We use 2D axisymmetric cylindrical coordinates with an adaptive mesh refinement (AMR) grid. The origin of the grid, $(0,0)$, is taken at the center of the explosion. In all the figures shown below the symmetry axis of the grid is the vertical axis. The axisymmetric grid forces us to neglect the orbital relative velocity of the He WD and the exploding CO WD. In any case, the orbital velocity is much smaller than the ejecta velocity, and will have virtually no
effect on our conclusions.

In our calculations we use high- and low-resolution grids. The low-resolution grid was designed to cover large distances, and was used to follow the evolution at late times of the case in which the He WD is less massive. Their respective resolution are the following ones. For the high-resolution simulations the minimum cell size is \( \sim 12 \times 12 \) km with a total of 10 levels of AMR refinement. For the low-resolution simulation the minimum cell size was \( \sim 150 \times 150 \) km at the beginning of the simulation and was lowered up to \( \sim 10,000 \times 10,000 \) km at the end of the simulation. This represent a change in the refinement level from 15 to 9.

The initial He WD mass, radius, and distance from the center of the explosion in the two simulated cases to be presented below are \((M_{\text{WD}}, R_{\text{WD}}, a_0) = (0.2M_\odot, 0.02R_\odot, 0.082R_\odot)\) and \((M_{\text{WD}}, R_{\text{WD}}, a_0) = (0.43M_\odot, 0.015R_\odot, 0.029 - 0.043R_\odot)\) for the low- and high-mass He WDs, respectively. The WDs are cold, and the radius of the 0.43\(M_\odot\) WD is somewhat smaller than the hotter WD presented in Fig. 1. These models were built with version 6022 of the Modules for Experiments in Stellar Astrophysics (MESA; Paxton et al. 2011). Initially, the ejecta is homologous expanding according to equations (1)-(3), with \(E_{51} = 1\) and \(M_{\text{SN}} = 1M_\odot\). The maximum velocity at the front of the ejecta is set to 20,000 km s\(^{-1}\). Its outer radius from the center of explosion is set to almost touch the He WD. In the figures described below time is measured from the moment at which the CO explodes. Finally, we mention that radiative cooling and photon diffusion are not important for the problem simulated here, and hence have not been included in our calculations.

### 4.2. A low-mass helium WD

In the case in which a low-mass He-WD is considered, nuclear reactions are not significant and three distinct stages of the interaction can be differentiated. (i) The early interaction phase, when temperatures of the shocked gas are at maximum, and the ejecta flows around the He WD. (ii) The intermediate phase, when the shock breaks out from the back of the WD and ejects helium from it. (iii) The late time phase, when expansion is homologous until the ejecta sweep a non-negligible ambient mass and adopts the shape of an old SNR. We ran the simulations using both the low- and high-resolution grids. This was done for checking numerical convergence. As mentioned earlier, the low-resolution grid was designed to cover a larger region around the interacting WDs, and thus was used to follow the evolution of the SNR at late times. In the overlapping regions, the results of the two simulations with different resolutions were found to be the same.
The early stage. In Fig. 2 we present the density and velocity maps at several times from \( t = 2 \) s (2 seconds after explosion) to the time instant at which the shock that runs through the He WD reaches the backside of the He WD \( (t = 16 \) s). The SN ejecta hits the WD and flows around it, forming a dense surface with a 3D conical shape. In our 2D grid the dense shell has a shape of two dense stripes on the meridional plane, one at each side of the symmetry axis. Note that as mentioned in section 3 the temperatures and densities are too low to drive any significant nuclear burning.

The intermediate stage. In Fig. 3 we show the flow after the break-out of the shock from the back side (down flow) of the He WD, and the consequent helium outflow. Most of the ejected helium falls back to the WD as can be seen in the last panel. Only \( 0.003M_\odot \) of helium escapes and flows outward near the symmetry axis, too small to be observed with current observational means. The strong concentration at the axis is a numerical effect. The volume inside the dense conical shell is a region of low density ejecta. The dense conical surface continues to expand and more or less preserves its shape in homologous expansion. The homologous expansion continues until the interaction with the ambient gas – the interstellar medium (ISM) or a circumstellar matter (CSM) – starts to shape the outskirts of the ejecta.

The late stage. We are interested in the morphology of the ejecta at hundreds of years after explosion. For numerical reasons, we let the ejecta interact with an ambient medium close to the explosion site. As the ejecta expansion is already homologous with high Mach numbers \(( \gtrsim 10)\) at the end of the intermediate stage, the morphology obtained here at the late stage and on a scale of several solar radii represents quite good the expected morphology hundreds of year later and with a much larger size (a few pc). For the scaled numerical study of the ejecta-ambient gas interaction we set the ambient density to be \( 0.01 \) g cm\(^{-3}\), and follow the expansion until \( t = 492 \) s, when the medium mass intercepted by the ejecta is \( \sim 1M_\odot \). The interaction of the dense conical surface with the ambient gas forms a circle of high pressure, with its center on the symmetry axis (half of this circle is into, and half out of, the page). This high pressure circle accelerates gas, both ambient and ejecta, toward the relatively empty cone (toward the symmetry axis). This gas and the helium along the symmetry axis, determine the flow structure within the cone.

To form a synthetic map (in radio, X-ray synchrotron, or thermal X-ray), we integrate over density squared along the lines of sight, but considering only shocked, hot gas. That is, we only consider gas with entropies \( S > 3 \times 10^9 \) erg K\(^{-1}\),

\[
I(x, y) \equiv \int [\rho(x, y, z)]^2dz,
\]

where \( x, y \) are the coordinates on the plane of the sky and \( z \) is taken along line of sight.
The obtained ‘intensity maps’ are presented in Fig. 5. Two inclinations are presented, the symmetry axis is in the plane of the sky (left), or at 30° to the plane of the sky (right). These are presented at two times when the swept-up ambient masses are $\sim 0.1 M_\odot$ ($t = 202$ s upper panels), and $\sim 1 M_\odot$ ($t = 492$ s lower panels). In Fig. 6 we present the integral of the density but only for the ejected mass,

$$N_{\text{eject}}(x, y) \equiv \int \rho(x, y, z)_{\text{eject}} dz$$

(9)

The prominent features of the SNR when the symmetry axis is close to the plane of the sky before the swept ISM gas is too large are the following ones. (a) A ‘flat front’ of the conical region (upper part in the figure which is the initial direction of the He WD); (b) A region of lower intensity at that flat front relative to the rest of the SNR front; (c) A dense conical surface in the interior; (d) The inner volume of the conical surface is almost completely devoid of ejecta gas. The first two features fade as more ambient gas (ISM) is swept. Let us note that the main result here does not depend much on whether the He WD is younger and hotter, hence has a larger radius. It will simply have somewhat larger orbital separation. But as the double-detonation model requires stable RLOF, the solid angle covered by the He WD will be about the same, and so is the conical shape formed behind it.

We are not aware of any SNR that has such a morphology. One might think of SN1006, but examining the prominent features we find that SN1006 cannot be explained by such an interaction. (a) SNR SN1006 has a flat front. However, there is a hydrogen-rich optical filament along the flat front. The flat front seems to have been formed by an asymmetrical external interaction formed by asymmetrical ISM. (b) In SN1006 the X-ray intensity of the flat front is lower than the front on the orthogonal directions, but not lower than the other side of the SNR (e.g., Winkler et al. 2014). Also, SN1006 does not show a uniform intensity along the spherical parts not including the flat front. (c) A dense conical surface in the interior is not observed in SN1006 (e.g., Winkler et al. 2014). (d) As can be seen from figure 9 of Winkler et al. (2014), the volume behind the flat front is rich in neon and oxygen, and it is not poor in ejecta. We conclude that the structure of the SNR SN1006, despite the flat front on one side, is incompatible with the morphology expected from the double-detonation scenario.
4.3. A massive helium WD

In this case we place a $0.43M_\odot$ He WD at closer distances than the $0.2M_\odot$ one, as described in section 4.1. We find that the helium WD is ignited when the distance of its center to the center of CO the WD is $\lesssim 3.1 \times 10^9$ cm = $0.045R_\odot$, and that practically no burning occurs if it is placed at larger distances.

In Figs. 7 to 9 we present the evolution of density, temperature, and nickel mass fraction, of the ignited He WD at 6 different times, as indicated. The initial distance of the center of the He WD from the center of explosion is $0.043R_\odot$. Note that this calculation shares some features in common with the evolution in the case in which a low-mass He WD is considered, but also some noticeable differences. In particular, although the evolution of the hydrodynamical flow is apparently similar, the key difference is the much larger temperatures attained during the interaction between the ejecta and the He WD. Ignition of helium occurs just before $t = 2$ s, as can be seen in the lower panels of Fig. 10. The ignited helium raises the temperature and a thermonuclear detonation occurs, in accordance with the theoretical estimates presented in section 3. By the last panel the explosion has ended.

It is interesting to note as well the important role of radiation pressure in this simulation, as it should be expected given the considerations explained in section 3. To corroborate this, in the upper panels of Fig. 11 we show the total pressure (top) and ratio of radiation to total pressure (bottom) at the time of helium ignition, $t = 2$ s. It can be seen that at the ignition point the radiation pressure dominates, but thermal pressure is not negligible. Also, the total pressure in the ignition region is $\sim 10^{22}$ erg cm$^{-3}$, comparable to the estimate given in equation (5) if we adopt $r_e = 0.04R_\odot$.

Given that the temperatures attained during the interaction between the ejecta and the massive He WD are rather high, extensive nuclear processing occurs, and a substantial amount of nickel is synthesized. Nickel first appears in a region laying between the center of the He WD and the surface facing the ejecta. Note that after a few seconds most of the material of the He WD has been processed to nickel. This contradicts observations, as the SNR will be highly asymmetrical, as in the violent merger simulation presented by Pakmor et al. (2012). We find that not all helium is burned and $\sim 0.15M_\odot$ of helium is ejected from the exploding He WD. This also contradicts observations. We conclude that the presence of a relatively close by, $a_0 \lesssim 0.45R_\odot$, He WD donor to the exploding CO WD leads to an explosion that has characteristics contradicting observations of SNe Ia. Accordingly, the double-detonation scenario seems to do not apply to normal SNe Ia.
5. SUMMARY AND CONCLUSIONS

We have studied the impact of the ejecta of an exploding CO WD on the donor star in the double-detonation scenario for the formation of Type Ia supernovae (SN Ia). We have done so for two masses of the secondary He WD, namely 0.2\text{M}_\odot and 0.43\text{M}_\odot, assuming that the SN Ia ejecta is already in homologous expansion when it hits the surface of the secondary WD. The first part of our study was done using analytical estimates, while in the second part of our work we performed full 2-dimensional hydrodynamical calculations, employing the FLASH code. Our most relevant results can be summarized as follows.

For the case in which a massive He WD (0.43\text{M}_\odot) is considered, our analytical estimates predicted that the material of the He WD would undergo a powerful thermonuclear runaway when the ejected material of the exploding CO interacts with outer layers of the donor WD (Sect. 3). Our analytical predictions are confirmed by our detailed hydrodynamical calculations that also give us the evolution with time of the flow, where ignition occurs, the amount of nickel formed, and the mass of helium ejected by the interaction (Figs. 7-10). In particular, the mass of ejected helium (0.15\text{M}_\odot) would have been easily detected in observations, implying that this scenario seems to be ruled out for standard SN Ia.

For the binary system containing a low-mass He WD (0.2\text{M}_\odot) no significant nuclear processing occurs, and the evolution consists of an almost pure hydrodynamical flow. The evolution can be divided in three distinct phases. During the initial phase a shock runs through the outer layers of the He WD, and the SN ejecta flows around the secondary star, forming a region with conical shape (Fig. 2). In the intermediate stage, just after the shock breaks-out from the back side of the He WD, some material from the He WD is ejected but most of it falls back at later times, while a conical dense surface continues expanding (Fig. 3). Finally, during the late stages of the evolution the SN ejecta interacts with the ambient medium, which we numerically set to a very high density to mimic interaction with the ISM hundreds of years later. During this phase the conical flow previously described forms a ring of high pressure, which accelerates material towards the low-density conical region (upper right panel of Fig. 4). The hydrodynamical evolution previously described has observational consequences. In an attempt to model the morphology of the resulting SNR we integrated the density squared of the hot gas for two viewing angles and two times (Fig. 5. The integrated ejecta density is shown in Fig. 6). We found that the shape of the SNR, that contains a prominent flat region in the direction of the shadow of the He WD, is at odds with known SNR morphologies.

In conclusion, our study supports previous claims that the double-detonation scenario can at best be responsible for a very small fraction of all SN Ia. Specifically, Piersanti et al. (2013) claimed that the double-detonation scenario can account for only a small fraction of all
SN Ia, because the parameter space leading to explosion is small. Ruiter et al. (2014), on the other hand, argued that the double-detonation model can account for a large fraction of SN Ia. For that to be the case, most (> 70%) of the donors in the study of Ruiter et al. (2014) are He WD. Our results show that He WD donors lead to explosions that are in contradiction with the observed morphology of the SNRs of Type Ia SN, and that if the He WD is massive (∼ 0.4M⊙), not all helium is burned and, consequently, would be spectroscopically observed, again in contradiction with observations.

There is another severe problem with the double detonation scenario (Tsebrenko & Soker 2014b). As Ruiter et al. (2014) showed, most exploding WDs in the double-detonation scenario are of mass < 1.1M⊙. This is in strong contrast with recent claims that most SN Ia masses are peak around 1.4M⊙ (Scalzo et al. 2014). Seitenzahl et al. (2013) also claimed that at least 50% of all SN Ia come from near Chandrasekhar mass (MCh) WDs.

All in all, we conclude that the double-detonation scenario can lead to explosions, but their characteristics are not typical of those of SN Ia. Thus, SNe Ia must be originated by other channels, most likely the core-degenerate and the double-degenerate scenarios (Tsebrenko & Soker 2014b).

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REFERENCES

Althaus, L. G., Panei, J. A., Romero, A. D., et al. 2009, A&A, 502, 207
Aznar-Siguán, G., García-Berro, E., Lorén-Aguilar, P., José, J., & Isern, J. 2013, MNRAS, 434, 2539
Badenes, C., Hughes, J. P., Bravo, E., & Langer, N. 2007, ApJ, 662, 472
Balick, B. 1987, AJ, 94, 671
Balick, B., & Frank, A. 2002, ARA&A, 40, 439
Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJ, 662, L95
Blair, W. P., Long, K. S., & Vancura, O. 1991, ApJ, 366, 484
Blondin, J. M., & Ellison, D. C. 2001, ApJ, 560, 244
Bloecher, T. 1995, A&A, 299, 755
Borkowski, K. J., Blondin, J. M., & Sarazin, C. L. 1992, ApJ, 400, 222
Borkowski, K. J., Sarazin, C. L., & Blondin, J. M. 1994, ApJ, 429, 710
Burkey, M. T., Reynolds, S. P., Borkowski, K. J., & Blondin, J. M. 2013, ApJ, 764, 63
Blair, W. P., Ghavamian, P., Long, K. S., et al. 2007, ApJ, 662, 998
Cassam-Chenaï, G., Decourchelle, A., Ballet, J., et al. 2004, A&A, 414, 545
Chiosi, E., Chiosi, C., Trevisan, P., Piovan, L., & Orio, M. 2014, arXiv:1409.1104
Dwarkadas, V. V., & Chevalier, R. A. 1998, ApJ, 497, 807
Fryxell B., Olson K., Ricker P., et al., 2000, ApJS, 131, 273
Guillochon, J., Dan, M., Ramirez-Ruiz, E., & Rosswog, S. 2010, ApJ, 709, L64
Hamers, A. S., Pols, O. R., Claeys, J. S. W., & Nelemans, G. 2013, MNRAS, 430, 2262
Han, Z., & Podsiadlowski, P. 2004, MNRAS, 350, 1301
Heng, K., & McCray, R. 2007, ApJ, 654, 923
Hoyle, F., & Fowler, W. A. 1960, ApJ, 132, 565
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
Ilkov, M., & Soker, N. 2012, MNRAS, 419, 1695
Ilkov, M., & Soker, N. 2013, MNRAS, 428, 579
Ji, S., Fisher, R. T., Garcia-Berro, E., et al. 2013, arXiv:1302.5700
Kashi, A., & Soker, N. 2011, MNRAS, 417, 1466
Katsuda, S., Tsunemi, H., Uchida, H., & Kimura, M. 2008, ApJ, 689, 225
Katz, B., & Dong, S. 2012, arXiv:1211.4584
Kinugasa, K., & Tsunemi, H. 1999, PASJ, 51, 239
Kushnir, D., Katz, B., Dong, S., Livne, E., & Fernández, R. 2013, arXiv:1303.1180
Levanon, N., Soker, N., & García-Berro, E. 2014, arXiv:1408.1375
Livio, M., & Riess, A. G. 2003, ApJ, 594, L93
Livne, E., & Arnett, D. 1995, ApJ, 452, 62
Lorén-Aguilar, P., Isern, J., & García-Berro, E. 2009, A&A, 500, 1193
Lorén-Aguilar, P., Isern, J., & García-Berro, E. 2010, MNRAS, 406, 2749
Nomoto, K. 1982, ApJ, 253, 798
Orlando, S., Bocchino, F., Miceli, M., Petruk, O., & Pumo, M. L. 2012, ApJ, 749, 156
Park, S., Slane, P. O., Hughes, J. P., et al. 2007, ApJ, 665, 1173
Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012, ApJ, 747, L10
Pakmor, R., Kromer, M., Taubenberger, S., & Springel, V. 2013, ApJ, 770, L8
Park, S., Badenes, C., Mori, K., et al. 2013, ApJ, 767, L10
Patnaude, D. J., Badenes, C., Park, S., & Laming, J. M. 2012, ApJ, 756, 6
Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJS, 192, 3
Piersanti, L., Tornambé, A., Yungelson, L., & Straniero, O. 2013, IAU Symposium, 281, 209
Prodan, S., Murray, N., & Thompson, T. A. 2013, arXiv:1305.2191
Raskin, C., & Kasen, D. 2013, arXiv:1304.4957
Raskin, C., Scannapieco, E., Fryer, C., Rockefeller, G., & Timmes, F. X. 2012, ApJ, 746, 62
Reynolds, S. P., Borkowski, K. J., Hwang, U., et al. 2007, ApJ, 668, L135
Ruiter, A. J., Belczynski, K., Sim, S. A., Seitenzahl, I. R., & Kwiatkowski, D. 2014, MNRAS, 440, L101
Sahai, R., & Trauger, J. T. 1998, AJ, 116, 1357
Scalzo, R. A., Ruiter, A. J., & Sim, S. A. 2014, MNRAS in press.
Schwarz, H. E., Corradi, R. L. M., & Melnick, J. 1992, A&AS, 96, 23
Seitenzahl, I. R., Cescutti, G., Röpke, F. K., Ruiter, A. J., & Pakmor, R. 2013, A&A, 559, L5
Shen, K. J., & Bildsten, L. 2009, ApJ, 699, 1365
Shen, K. J., & Bildsten, L. 2014, ApJ, 785, 61
Shen, K. J., Guillochon, J., & Foley, R. J. 2013, ApJ, 770, L35
Soker, N. 2011, arXiv:1109.4652
Soker, N., Kashi, A., García-Berro, E., Torres, S., & Camacho, J. 2013, MNRAS, 431, 1541
Soker, N., García-Berro, E., & Althaus, L. G. 2014, MNRAS, 437, L66
Sollerman, J., Ghavamian, P., Lundqvist, P., & Smith, R. C. 2003, A&A, 407, 249
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Thompson, T. A. 2011, ApJ, 741, 82
Tornambé, A., & Piersanti, L. 2013, MNRAS, 431, 1812
Tsebrenko, D., & Soker, N. 2014a, arXiv:1407.6231
Tsebrenko, D., & Soker, N. 2014b, arXiv:1409:0780
Tylenda, R. 1983, A&A, 126, 299—
van Kerkwijk, M. H., Chang, P., & Justham, S. 2010, ApJ, 722, L157
Vink, J. 2008, ApJ, 689, 231
Wang, C.-Y., & Chevalier, R. A. 2001, ApJ, 549, 1119
Warren, D. C., & Blondin, J. M. 2013, MNRAS, 429, 3099
Webbink, R. F. 1984, ApJ, 277, 355
Whelan, J., & Iben, I., Jr. 1973, ApJ, 186, 1007
Winkler, P. F., Williams, B. J., Reynolds, S. P., Petre, R., Long, K. S., Katsuda, S., Hwang, U. 2014, ApJ, 781, 65
Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371

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Fig. 1.— Pressure and density profiles of a 0.43 $M_\odot$ He WD, as a function of the mass coordinate $\log(1 - M_r/M_{\text{WD}})$. This coordinate allows to better resolve the very outer layers of the star, where the effects of the shock are presumably more important. The central temperature of the WD is $10^7$ K.
Fig. 2.— Density maps in the meridional plane at 6 times for the case in which a $0.2 M_\odot$ WD is adopted. The time elapsed since explosion is indicated in each panel. The simulation starts 2 s after explosion. The symmetry axis is along the left edge, and the origin of the grid is at the center of the exploding CO WD. The blue line encloses the volume where the local helium mass fraction is $Y > 0.5$; this represents the He WD and the material removed from the He WD. Prominent features include a shock running around the WD, and the formation of a dense conical surface in the expanding ejecta. The shock just reaches the back edge of the He WD at $t = 16$ s. Temperatures and densities are too low to drive any significant nuclear burning. The plots are from the high-resolution run. The lower resolution simulation results in a similar structure. Velocity is proportional to the arrow length, with the inset showing an arrow for 10,000 km s$^{-1}$. 
Fig. 3.— Same as Fig. 2 for later times, the intermediate stage. The shock breaks out from the rear of the WD, ejecting helium. Only 0.003$M_\odot$ of helium escapes while most of the helium falls back on the WD as can be seen in the last panel. The plots are from the low-resolution run. Velocity is proportional to the arrow length, with the inset showing an arrow for 10,000 km s$^{-1}$. 
Fig. 4.— Density maps in the meridional plane at 6 late times for the case in which a 0.2$M_\odot$ WD is adopted. The computational grid was folded around the axis to present the entire meridional plane. A homologous expansion of the ejecta, with a Mach number $> 10$, has developed by the beginning of this evolutionary phase, with a dense conical surface surrounding a conical volume almost completely devoid of SN ejecta. The ambient gas density is fixed by our requirement that at the end of the simulation the ejecta sweeps a substantial mass (see text). At the end of our simulations, $t = 492$ s, the SN ejecta has swept 1$M_\odot$ of ambient gas. As the outflow of the ejecta is already homologous, the morphology obtained here mimics that at hundreds of years later. The small features along the symmetry axis itself, both at the top and bottom of the SN-ISM interaction, are numerical artifacts.
Fig. 5.— Synthetic observed morphology (eq. [3]) of the resulting SNR for the case of a low-mass He WD. We show the intensity map described in the main text, and only for the high-temperature gas. The $x$ and $y$ coordinates are the coordinates on the plane of the sky, and the $z$ coordinate is taken along line of sight. Two inclinations are presented, the symmetry axis is in the plane of the sky (left), or at $30^\circ$ to the plane of the sky (right). These are presented at two times, namely when the swept-up ambient masses are $\sim 0.1 M_\odot$ ($t = 202$ s upper panels), and $\sim 1 M_\odot$ ($t = 492$ s lower panels). As the outflow of the ejecta is already homologous at the beginning of this phase, the morphologies obtained here mimic that at hundreds of years later when the ejecta interacted with $\sim 0.1 - 1 M_\odot$ of homogeneous ambient medium (CSM or ISM).
Fig. 6.— The integrated ejected mass (eq. [9]) for the two times as in Fig. 5 and for the symmetry axis at 30° to the plane of the sky.
Fig. 7.— Density maps in the meridional plane at six times for a He WD of $0.43M_\odot$ at an initial distance of its center to the center of explosion of $0.045R_\odot$. Note that at $t = 2$ s helium is ignited and an explosion occurs in the He WD. The velocities are proportional to the arrow length, with the inset showing an arrow for $10,000$ km s$^{-1}$. 
Fig. 8.— Same as Fig. 7 but for temperature.
Fig. 9.— Same as Fig. 7 but for the nickel mass fraction. Ignition of helium in the He WD occurs just before $t = 2$ s.
Fig. 10.— Total pressure (top left), ratio of radiation to total pressure (top right), temperature (bottom left), and density (bottom right) at $t = 2$ s. The velocities are proportional to the arrow length, with the inset showing an arrow for 10,000 km s$^{-1}$. The blue line shows when the helium fraction is $Y = 0.5$. The figure is for the case in which a He WD of mass $0.43M_\odot$ is adopted.