Constraining the double-degenerate scenario for Type Ia supernovae from merger ejected matter

Naveh Levanon\textsuperscript{1}, Noam Soker\textsuperscript{1}, and Enrique García–Berro\textsuperscript{2,3}

ABSTRACT

We follow the mass blown during the WD-WD merger process in the Double-Degenerate (DD) scenario for type Ia supernovae (SN Ia), and find that the interaction of the SN ejecta with this wind affects the early ($< 1$ day) light curve in a way that may contradict observations, if the detonation occurs during or shortly after the merger ($< 1$ day). The main source of the blown mass is a disk-wind, or jets that are launched by the accretion disk around the more massive WD. This disk-originated matter (DOM) will be shocked by the SN ejecta and kinetic energy will be channeled to thermal energy and then to additional radiation. The radiation could be interpreted as an explosion originating from a progenitor having a radius of one solar radius or more, contradicting observations of SN 2011fe.

Subject headings: accretion, accretion disks — binaries: close — hydrodynamics — supernovae: general — white dwarfs

1. INTRODUCTION

There is no consensus on the evolutionary routes that bring white dwarfs (WDs) to undergo a carbon-oxygen thermonuclear detonation and become type Ia supernovae (SN Ia; e.g., Livio 2001; Maoz 2010; Howell 2011; Maoz et al. 2014). The different scenarios currently considered in the literature can be divided in several ways, depending on the criterion used. We classify the scenarios into five groups. (a) The double degenerate (DD) scenario (e.g., Webbink 1984; Iben & Tutukov 1984). In this scenario the merger of two WDs orbiting each other in

\textsuperscript{1}Department of Physics, Technion – Israel Institute of Technology, Haifa 32000 Israel; nlevanon@tx.technion.ac.il, soker@physics.technion.ac.il

\textsuperscript{2}Departament de Física Aplicada, Universitat Politècnica de Catalunya, c/Esteve Terrades 5, 08860 Castelldefels, Spain

\textsuperscript{3}Institute for Space Studies of Catalonia, c/Gran Capità 2-4, Edif. Nexus 201, 08034 Barcelona
a binary system, and losing angular momentum and energy through the radiation of gravitational waves (Tutukov & Yungelson 1979), leads to the explosion. The exact time after merger when explosion occurs is unknown, and different mechanisms are discussed in the literature (e.g., van Kerkwijk et al. 2010). This scenario can account for sub-Chandrasekhar explosions as well (e.g., van Kerkwijk et al. 2010; Badenes & Maoz 2012). In recent years a violent merger process was discussed as a channel to ignite the WD (e.g., Lorén-Aguilar et al. 2010; Pakmor et al. 2013; Aznar-Siguán et al. 2013). Others consider a very long delay from merger to explosion, e.g., because rapid rotation keeps the structure overstable (Tornambé & Piersanti 2013). (b) The core-degenerate (CD) scenario (Livio & Riess 2003; Kashi & Soker 2011; Ilkov & Soker 2012, 2013; Soker et al. 2013, 2014). In this scenario a WD merges with a hot core of a massive asymptotic giant branch (AGB) star. The explosion can occur shortly after the common envelope phase, hence leading to a SN Ia inside a planetary nebula (Tsebrenko & Soker 2013, 2014), or a very long time delay. There is some overlap between the DD and CD scenarios. (c) The single degenerate (SD) scenario (e.g., Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004). According to this scenario a WD accretes mass from a non-degenerate stellar companion. After the WD reaches the Chandrasekhar mass it explodes. There is also the scenario for accretion of helium-rich material from a non-degenerate helium star (e.g., Iben et al. 1987; Ruiter et al. 2011), which we list under the double-detonation scenario. (d) The double-detonation (DDet) mechanism (e.g., Woosley & Weaver 1994; Livne & Arnett 1995), in which a sub-Chandrasekhar mass WD accumulates on its surface a layer of helium-rich material, which can detonate and lead to a second detonation near the center of the CO WD. One version has a helium WD as the donor star (e.g., Shen et al. 2013 for a recent paper). Piersanti et al. (2013) point out that this scenario can at most explain a small fraction of all SN Ia, and Papish et al. (2014) find the SN remnants (SNRs) of this scenario to have a large departure from spherical symmetry, contradicting observations. (e) The WD-WD collision scenario (e.g., Thompson 2011; Katz & Dong 2012; Kushnir et al. 2013). In this scenario a tertiary star brings two WDs to collide. The collision sets 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).

Each of these scenarios has some problems, and in some cases these are severe (Soker et al. 2014). Our view, based on the comparison table of Soker et al. (2014), is that the most promising are the DD and CD scenarios. With this view in mind, we aim in this paper to study the circumstellar matter (CSM) that is expected to be blown during the merger process in the DD scenario. To distinguish CSM that might have been expelled prior to the merger process from the material expelled from the accretion disk formed during the merger process, we term the latter disk-originated matter (DOM). In this paper we study the process of WD-WD merger in the DD scenario, post-

\[\text{http://grb.physics.ncsu.edu/FOE2013/WEB/abstracts.html}\]
poning the core-WD merger to a future paper. In section 2 we list some previous studies of the DD scenario where a CSM or an extended envelope are formed. In section 3 we concentrate on the formation of the DOM, and in section 4 we study the implications of an explosion inside the DOM and compare the different cases with observations. Discussion and short summary are in section 5.

2. PREVIOUS STUDIES OF PRE-EXPLOSION CSM

Numerous studies (e.g. Yoon et al. 2007; Lorén-Aguilar et al. 2009; Dan et al. 2011; Pakmor et al. 2012b; Raskin et al. 2012; Ji et al. 2013; Zhu et al. 2013) have used smoothed particle hydrodynamics (SPH) simulations to evolve a binary WD system from first contact through dynamical merger until the complete destruction of the donor. This is referred to as the dynamical phase of the merger. The typical WD masses in these simulations were in the range 0.2 $M_\odot$ to 1.2 $M_\odot$, with appropriate compositions of He, CO or ONe. Some of these simulations are summarized in Table I which also presents our suggested outflow structure and some observational consequences that are discussed in the following sections.

While different initial and end conditions are used for these simulations, most results are rather consistent across studies. After a time $t_{\text{dyn}} \sim 100$ s that corresponds to several orbital periods, the donor is completely disrupted. The merged product consists of the more massive primary WD, almost intact, with the material of the donor residing in a hot corona surrounding it and in a nearly Keplerian disk extending out to $\sim 0.1 R_\odot$. The mass of the donor is split roughly in half between the corona and the disk (e.g. Lorén-Aguilar et al. 2009). In addition, a tidal tail with a mass of $\sim 10^{-3} M_\odot$ is unbound from the system (e.g. Raskin & Kasen 2013).

A different possible outcome is the violent merger scenario of Pakmor et al. (2012b). They found that during the dynamical merger of a 1.2 $M_\odot + 0.9$ $M_\odot$ system hotspots are formed in which carbon ignition can lead to thermonuclear runaway. The resulting explosion on the surface of the accreting WD is highly asymmetrical, and Pakmor et al. (2012b) compared this with regular SNIa by taking angle-averaged lightcurves and spectra. However, such largely asymmetrical explosions are in contradiction with resolved SNR in the Galaxy and the Magellanic clouds (Lopez et al. 2011). Moll et al. (2014) found that the variations in light-curves and spectra with viewing angle of explosions triggered by a violent merger are larger than observed variations. Dan et al. (2014) investigated a large range of merger masses and found that the violent merger scenario is only plausible for systems with a total mass of $> 2.1 M_\odot$, though they used a relatively small number of smoothed particles, which means nuclear processes are underestimated (Pakmor et al. 2012a).

An important property of systems following the dynamical merger is a clear hierarchy of timescales. The dynamical timescale of the merger $t_{\text{dyn}} \sim \Omega^{-1}$ is of the order of seconds. Next in
|                  | A                              | B                              | C                              | D                              | E                              |
|------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| **Papers**       | Shen et al. (2012), Schwope et al. (2012) | van Kerkwijk et al. (2010), Zhu et al. (2013) | Ji et al. (2013), Beloborodov (2013) | Pakmor et al. (2012b) This paper |
| Fiducial system ($M_\odot$) | 0.9 ± 0.6 | 0.6 ± 0.6 | 0.6 ± 0.6 | 1.2 ± 0.9 | None |
| **Assumptions**  | Axisymmetry; α-viscosity | Spherical, wind carries all AM with $E = 0$ | Axisymmetry; MRI viscosity | Off-center hotspots detonate during merger | AM carried by jets or disk-wind with a terminal velocity of $v_{\text{esc}}(R_{\text{rem}}) \sim 10^4$ |
| $L_{\text{acc}}$ ($M_\odot$) | $1 \times 10^4$ | N/A | $2 \times 10^4$ | N/A | N/A |
| Remnant star $a$ | $M_{\text{rem}}$ ($M_\odot$) | 1.04 | 0.96 or 0.91 | 1.12 | 2 | $\sim 1 - 1.5$ |
| $R_{\text{rem}}$ ($R_\odot$) | 0.007 | 0.01 or 0.02 | 0.03 | 0.03 | $\leq 0.02$ |
| Explosion        | No explosion. Steady carbon burning. | Explosion in similar-mass systems, no explosion in nonsimilar-mass systems | Unclear | Explosion during dynamical merger | Explosion is assumed to check consequences |
| Expanded envelope $b$ | $M_{\text{env}}$ ($M_\odot$) | 0.46 | N/A | 0.06 | N/A | N/A |
| $R_{\text{env}}$ ($R_\odot$) | 1.4 | N/A | 0.14 | N/A | N/A |
| Disk-Wind (DOM) $c$ | $M_{\text{DOM}}$ ($M_\odot$) | $6 \times 10^{-6}$ | 0.25, 0.29 | $10^{-3}$ | $5 \times 10^{-3}$ | 0.04 |
| $v_{\text{DOM}}$ ($\text{km s}^{-1}$) | N/A | $\sim 2000$ | $\sim 3000$ | $\sim 2000$ | $\sim 5000$ |

**Table 1. Comparison of outcomes of the DD scenario**

Note. — AM = angular momentum. $v_{\text{esc}}$ is the escape velocity from the remnant during the accretion phase $v_{\text{esc}} = \sqrt{2GM_{\text{rem}}/R_{\text{rem}}}$.

$a$ The primary with the accreted mass from the disk (not the SNR).

$b$ Material surrounding the accreting WD.

$c$ Material blown by the accretion disk, termed here DOM for disk-originated matter. In all systems an additional $\sim 10^{-3}$ $M_\odot$ is unbounded during the dynamical merger phase in the tidal tail.

$d$ Material is ejected with zero total energy. $v_{\text{DOM}} = v_{\text{esc}} (R_{\text{DOM}})$.

$e$ Material is ejected with a terminal velocity of $v_{\text{DOM}} = v_{\text{esc}} (R_{\text{ DOM}})$. 

Explosions in similar-mass systems, no explosion in nonsimilar-mass systems. Unclear

$\sim 1 - 1.5$

Explosion during dynamical merger

Explosion is assumed to check consequences

Optically thick DOM at $\sim 1 - 10 R_\odot$ contracts.

SN 2011fe (Bloom et al. 2013; Piro & Nakada 2013)

DOM is expected to SN 2011fe (see Section 4).

Highly asymmetrical explosion; contractions resolved Type Ia SNR (Lopez et al. 2013)

Such an outflow contradicts SN 2011fe (see Section 4).
order of magnitude is the viscous timescale of the accretion disk, which characterizes the transport of disk mass inwards and angular momentum outwards. Modelling of this "viscous phase" in the merger usually uses the Shakura-Sunyaev $\alpha$-prescription \cite{ShakuraSunyaev1973}, giving a timescale of $t_{\text{visc}} \sim \alpha^{-1} (R_{\text{disk}}/H) t_{\text{dyn}}$ with $R_{\text{disk}}$, $H$ and $t_{\text{dyn}}$ the disk radius, scale height and dynamical timescale, respectively (e.g. \cite{vanKerkwijk2010}). Taking a suitable value of $\alpha = 0.01 - 0.1$ gives a viscous timescale of $t_{\text{visc}} \sim 10^3 - 10^4$ s. Largest in the timescale hierarchy is the thermal timescale of the merger product, which can vary depending on the possible existence of stable carbon burning but is always of the order of years or above. This timescale hierarchy $t_{\text{dyn}} \ll t_{\text{visc}} \ll t_{\text{th}}$ justifies the breakdown of studies into the different merger phases, taking different assumptions for each. We focus on the implications of an explosion occurring during or after the viscous phase. Our results do not apply to models where the delay between merger and explosion is very long, up to millions of years, as expected if rotation keeps the remnant overstable (e.g. \cite{TornambéPiersanti2013}).

\cite{Schwab2012} and \cite{vanKerkwijk2010} investigated the evolution of the merger product following the dynamical phase. \cite{Schwab2012} continued their preliminary numerical study \cite{Shen2012} and using the SPH models of \cite{Dan2011} evolved the merger product until it reached a spherical end state, typically after $\sim 10^4$ s. The viscosity transports most of the angular momentum outward to large distances and the merger develops into a quasi-spherical object, with part of the disk inflated to distances exceeding $10 R_\odot$. The hot envelope of the merged WD is further heated during the viscous phase, reaching conditions for stable carbon burning. Of the various systems studied, none exhibits conditions for a dynamical burning time leading to a runaway explosion.

\cite{vanKerkwijk2010} explored the evolution through the viscous phase by assuming spherical symmetry and using MESA \cite{Paxton2011} to evolve a $0.6 M_\odot + 0.6 M_\odot$ system from \cite{Loren-Aguilar2009}. In \cite{Zhu2013} the study was expanded to include a set of initial binary masses, modelling the dynamical phase with SPH and porting the end results to spherical models under several assumptions. The SPH-to-MESA port consisted of building an entropy profile by averaging along equipotentials, and finding a spherical model with the same total energy as the SPH end model. The difference in mass (the spherical model always has a lower mass) was taken to be the mass expelled during the viscous phase, taking with it all angular momentum. For their fiducial $0.8 M_\odot + 0.4 M_\odot$ system, a mass of 0.25 $M_\odot$ was expelled - a value much higher than for similar systems in \cite{Schwab2012}. If the assumptions driving the \cite{vanKerkwijk2010} spherical modelling are accepted for the merged object, then the removed mass is the matter from the disk that does not undergo accretion because of angular momentum conservation, with the mass loss mechanism left unspecified. This matter is by definition marginally unbound, and can correspond to the giant structure of \cite{Schwab2012}, which is not unbound but is significantly extended around the degenerate merger.
Several studies focused on the effect of magnetic fields during the merger. Ji et al. (2013) used a $0.6 \, M_\odot + 0.6 \, M_\odot$ dynamical merger from Lorén-Aguilar et al. (2009) and evolved it in 2D with FLASH, including an initial vector potential term suited for the magneto-rotational instability (MRI; Balbus & Hawley 1991). Their simulations confirm the importance of the MRI in redistributing angular momentum and driving accretion and outflow from the disk. They find an effective Shakura-Sunyaev $\alpha$-parameter converging to $\alpha \sim 0.01$, comparable to the value $\alpha = 0.03$ chosen by Schwab et al. (2012). The inclusion of magnetic fields means that shear energy is not only locally dissipated in the disk, but is also converted to magnetic energy which eventually heats a more extended corona. They find that a total mass of $\sim 10^{-3} \, M_\odot$ is unbound from the disk during accretion and expelled at a mean velocity of $\sim 2600 \, \text{km s}^{-1}$. Beloborodov (2013) reproduced these results from basic principles, obtaining comparable mass and velocity for matter expelled from the magnetic corona. In addition Beloborodov (2013) predicted that this mass loss will lead to a detectable transient with $L \sim 10^{41} - 10^{42} \, \text{erg s}^{-1}$ during $t_{\text{visc}}$.

In the studies mentioned above, a strong constraint on any possible explosion during the viscous phase is the existence of substantial disk-originated matter (DOM) in the vicinity of the exploding object. The collision of exploded ejecta with the DOM will influence the inferred size of the exploding object, making it $\gtrsim 1 \, R_\odot$. For the fiducial model of Schwab et al. (2012), the DOM is opaque up to $> 1 \, R_\odot$, as evident from their graphs. For the models of Zhu et al. (2013) the same holds, as will be shown in the next section. This is a problematic result for regular SNIa, whose size is an order of magnitude smaller, e.g. SN 2011fe (e.g., Nugent et al. 2011; Bloom et al. 2012; Piro & Nakar 2014). We now turn to study the observational signatures of this DOM.

### 3. REMOVAL OF DISK MATERIAL

We consider here a model with the assumption, based on stellar winds and velocities of jets from accretion disks, that the terminal velocity of the wind equals the escape velocity from the vicinity of the more massive WD

$$v_{\text{DOM}} \simeq v_{\text{terminal}} \simeq v_{\text{esc}} (R_{\text{rem}}) \simeq 5000 \, \text{km s}^{-1},$$

where $R_{\text{rem}}$ is the radius of the remnant during the accretion phase. We assume spherical symmetry as well, despite the expectation for a bipolar structure due to jets and/or disk winds. The radius of the DOM is

$$R_{\text{DOM}} \simeq v_{\text{DOM}} t = 72 \left( \frac{v_{\text{DOM}}}{5000 \, \text{km s}^{-1}} \right) \left( \frac{t}{10^4 \, \text{s}} \right) R_\odot.$$  

Mass is expelled at a range of velocities, so it will be useful to define the average DOM density

$$\bar{\rho}_{\text{DOM}} \simeq 1.5 \times 10^{-7} \left( \frac{M_{\text{DOM}}}{0.04 \, M_\odot} \right) \left( \frac{v_{\text{DOM}}}{5000 \, \text{km s}^{-1}} \right)^{-3} \left( \frac{t}{10^4 \, \text{s}} \right)^{-3} \, \text{g cm}^{-3},$$
where $M_{\text{DOM}}$ is the expelled mass. The value taken for this mass is based on the typical ratio of mass outflow rate in jets to accretion rate in systems observed to launch jets, $\sim 5 - 10\%$, and on a typical WD companion mass of $0.4 - 0.8 \, M_\odot$. Taking free electron scattering opacity ($\kappa_T = 0.2 \, \text{cm}^2 \, \text{g}^{-1}$) as a lower bound, the optical depth is

$$\tau \gtrsim \kappa_T \tilde{\rho}_{\text{DOM}} r_{\text{DOM}} = 1.5 \times 10^5 \left( \frac{M_{\text{DOM}}}{0.04 \, M_\odot} \right) \left( \frac{v_{\text{DOM}}}{5000 \, \text{km s}^{-1}} \right)^{-2} \left( \frac{t}{10^4 \, \text{s}} \right)^{-2} \left( \frac{\kappa}{\kappa_T} \right).$$

(4)

This shows that the wind-blown DOM is opaque throughout the viscous phase. If an explosion takes place inside this wind, it will be observed as an explosion of an object of size $\gtrsim 1 \, R_\odot$, in contradiction with SN 2011fe whose progenitor radius is limited to $R \lesssim 0.1 \, R_\odot$ (Bloom et al. 2012; Piro & Nakar 2014). This will be elaborated upon in the next section. Note that the wind-blown DOM is opaque even if a much smaller mass ($\sim 10^{-3} \, M_\odot$) is blown, such as through tidal tail formation (Raskin & Kasen 2013) or magnetized outflow (Ji et al. 2013; Beloborodov 2013), though for these examples the mass loss is far from spherical.

Zhu et al. (2013) use different assumptions on the expelled material during the viscous phase. The DOM is assumed to leave with zero total energy and so has an outflow velocity of $v_{\text{esc}} = \sqrt{2GM_{\text{rem}}/R_{\text{DOM}}}$, where $M_{\text{rem}}$ is the remnant mass. The mass of the DOM is also larger, $\sim 0.2 \, M_\odot$. This leads to a more compact DOM, of radius

$$R_{\text{DOM}} \simeq \left( \frac{3}{2} \sqrt{2GM_{\text{rem}}} \cdot t + R_\odot^3 \right)^{\frac{1}{3}} \approx 5.6 \left( \frac{M_{\text{rem}}}{1 \, M_\odot} \right)^{\frac{1}{3}} \left( \frac{t}{2 \times 10^4 \, \text{s}} \right)^{\frac{1}{3}} R_\odot,$$

(5)

so the density of the DOM is higher and it is likewise opaque throughout the viscous phase.

4. EXPLOSION INSIDE DISK-ORIGINATED MATTER (DOM)

If the merger remnant would explode during the viscous phase of the accretion disk as in the scenario proposed by van Kerkwijk et al. (2010), the high-velocity exploded material (ejecta) will shock the DOM and generate an observable signal. We discuss here two effects of the shocked DOM on observations. (1) The extra thermal energy in the shocked DOM will lead to a larger inferred progenitor radius. (2) The passage of the shock wave through the DOM will generate a transient signal.

4.1. Inferred Progenitor Radius

The fresh SN ejecta is radiation-dominated, and adiabatic expansion reduces thermal energy as $1/r$. By $1 \, R_\odot$ the thermal energy is reduced to $\sim 0.02$ times its initial value for an initial
WD radius of $R_{\text{WD}} = 0.02 \, R_\odot$. In our model the DOM, with a mass of $M_{\text{DOM}} \sim 0.04 \, M_\odot$, is shocked at $R_{\text{DOM}} \sim 10 - 100 \, R_\odot$. The relative velocity between the DOM, with $v_{\text{DOM}} \lesssim 5000 \, \text{km s}^{-1}$, and the ejecta, with $v_{\text{ej}} \sim 15,000 \, \text{km s}^{-1}$, implies that the amount of kinetic energy that is transferred to thermal energy during the collision is $E_{\text{shock}} \simeq 5 \times 10^{50} (M_{\text{DOM}}/M_\odot)$ erg. This can be much larger than the thermal energy of the ejecta just before it hits the DOM, $\simeq 5 \times 10^{50} (R_{\text{prog}}/R_{\text{DOM}})$ erg, where $R_{\text{prog}}$ is the progenitor’s radius. We took the initial thermal energy of the exploding WD to be half the explosion energy (the rest is kinetic energy).

When the thermal energy content of the gas is used to infer the initial radius at later times, by using the radiation before $^{56}\text{Ni}$ decay becomes dominant (e.g., Nugent et al. 2011), the observations will be interpreted as if the progenitor radius was

$$R_{\text{prog,i}} \gtrsim R_{\text{DOM}} \frac{M_{\text{DOM}}}{M_{\text{WD}}} = 0.3 \left( \frac{R_{\text{DOM}}}{10 \, R_\odot} \right) \left( \frac{M_{\text{DOM}}}{0.04 \, M_\odot} \right) \left( \frac{M_{\text{WD}}}{1.4 \, M_\odot} \right)^{-1} \, R_\odot. \quad (6)$$

Such a large radius is ruled out for SN 2011fe (e.g. Nugent et al. 2011; Bloom et al. 2012; Piro & Nakar 2014). The constraints on SN 2011fe of $R_{\text{WD}} \lesssim 0.1 \, R_\odot$ limits the DOM mass at $R_{\text{DOM}} \sim 100 \, R_\odot$ to $\lesssim 10^{-3} \, M_\odot$. Note that using the more massive and compact DOM derived from the Zhu et al. (2013) model gives an inferred progenitor radius, $R_{\text{prog,i}} \simeq 0.7 \, R_\odot$, which also exceeds the constraint on SN 2011fe.

The derivation of equation (6) assumes that the thermal energy due to the ejecta-DOM collision is distributed in the entire ejecta, as the thermal energy in the explosion itself. However, the thermal energy of the collision is distributed in the DOM and the outer part of the ejecta. The radiation that diffuses out comes from these outer parts. This implies that thermal energy that is radiated at early hours is much larger than if the thermal energy would have been distributed in the entire ejecta. Consequently, the value given in equation (6) is a lower bound on the inferred progenitor radius at early hours.

### 4.2. Transient UV Signal

The front of the SN ejecta moves at a velocity of $\sim 20,000 \, \text{km s}^{-1}$. A typical value for the velocity of the ejecta shocking the DOM is found by taking an exponential density profile for the ejecta (Dwarkadas & Chevalier 1998) and searching for the velocity above which the total mass of the ejecta is about $M_{\text{DOM}} \sim 0.04 \, M_\odot$. This gives $v_{\text{ej}} \simeq 15,000 \, \text{km s}^{-1}$. The shock passes through the DOM in a dynamical time

$$t_{\text{dyn}} \simeq 5 \times 10^3 \left( \frac{v_{\text{ej}} - v_{\text{DOM}}}{2 v_{\text{DOM}}} \right)^{-1} \left( \frac{\Delta t_{\text{exp}}}{10^4 \, \text{s}} \right) \, \text{s,} \quad (7)$$
where $\Delta t_{\text{exp}}$ is the time between the beginning of DOM formation in the viscous phase and the explosion.

After ejecta-DOM collision, expansion continues, and most of the thermal energy is lost to adiabatic expansion of the DOM and ejecta, now a combined medium. Mostly photons which can diffuse on a time shorter than about $t_{\text{dyn}}$ will escape. More photons will diffuse later, and lead to the inferred large progenitor radius as discussed in section 4.1. The diffusion time is given by

$$t_{\text{dif}} = \frac{\tau_{\text{dif}}}{3} = \frac{\ell_{\text{dif}}^2}{3c} = \frac{\rho_{\text{DOM}} \rho_s}{3c} \left( \frac{M_{\text{DOM}}}{0.04 \, M_\odot} \right)^{-\frac{1}{2}} \left( \frac{\Delta t_{\text{exp}}}{10^4 \, \text{s}} \right)^{\frac{1}{2}} \left( \frac{v_{\text{ej}}}{15000 \, \text{km s}^{-1}} \right)^{\frac{1}{2}} \left( \frac{v_{\text{ej}} - v_{\text{DOM}}}{2v_{\text{DOM}}} \right)^{-2} \left( \frac{\kappa}{\kappa_T} \right)^{-\frac{1}{2}} R_\odot. \quad (8)$$

(e.g. Kasen 2010), where $\rho_s$ is the shocked DOM density and $l_{\text{dif}}$ is the layer through which photons diffuse. For a radiation pressure dominated gas, $\rho_s = 7 \rho_{\text{DOM}}$. Equating $t_{\text{dif}} = t_{\text{dyn}}$ and using $\rho_{\text{DOM}} \approx \bar{\rho}_{\text{DOM}}$ gives a diffusion distance of

$$l_{\text{dif}} \approx 1.2 \left( \frac{M_{\text{DOM}}}{0.04 \, M_\odot} \right)^{-\frac{1}{2}} \left( \frac{\Delta t_{\text{exp}}}{10^4 \, \text{s}} \right)^{\frac{1}{2}} \left( \frac{v_{\text{ej}}}{15000 \, \text{km s}^{-1}} \right)^{\frac{1}{2}} \left( \frac{v_{\text{ej}} - v_{\text{DOM}}}{2v_{\text{DOM}}} \right)^{-2} \left( \frac{\kappa}{\kappa_T} \right)^{-\frac{1}{2}} R_\odot. \quad (9)$$

The diffusion distance cannot be larger than the length of the shocked DOM, which is approximately $l_{\text{DOM},\text{shocked}} \approx 0.1 R_\odot$. The last equation and the following ones assume that indeed $l_{\text{dif}} \leq l_{\text{DOM},\text{shocked}}$, which is valid therefore for $\Delta t_{\text{exp}} \lesssim 10^5 \, \text{s}$. For a larger $\Delta t_{\text{exp}}$, instead of equation (9) we have $l_{\text{dif}} \approx l_{\text{DOM},\text{shocked}}$. The energy density in the diffusion volume is $\epsilon_s = 3 \rho_s$. Since the density of the unshocked DOM is much less than that of the ejecta, the pressure of the shocked gas is roughly the ram pressure,

$$p_s \approx \frac{6}{7} \rho_{\text{DOM}} \left( v_{\text{ej}} - v_{\text{DOM}} \right)^2. \quad (10)$$

The diffusion volume is a shell of thickness $l_{\text{dif}}$ at a radius of $R_{\text{DOM}}$. The radiation energy diffusing outwards from this volume is

$$E \approx 0.5 \cdot 0.5 \cdot 3 \rho_s \cdot 4 \pi R_{\text{DOM}}^2 l_{\text{dif}} \approx 1.7 \times 10^{48} \left( \frac{M_{\text{DOM}}}{0.04 \, M_\odot} \right)^{\frac{1}{2}} \left( \frac{\Delta t_{\text{exp}}}{10^4 \, \text{s}} \right)^{\frac{1}{2}} \left( \frac{v_{\text{ej}}}{15000 \, \text{km s}^{-1}} \right)^{\frac{1}{2}} \left( \frac{v_{\text{DOM}}}{5000 \, \text{km s}^{-1}} \right) \left( \frac{v_{\text{ej}} - v_{\text{DOM}}}{10000 \, \text{km s}^{-1}} \right) \left( \frac{\kappa}{\kappa_T} \right)^{-\frac{1}{2}} \text{erg}, \quad (11)$$

where a factor of 0.5 was taken to account for half of the photons diffusing inwards, and another factor of 0.5 was taken to account for roughly half of the energy being diffused, with the remainder going to adiabatic expansion. The average luminosity during $t_{\text{dyn}}$ is

$$L \approx \frac{E}{t_{\text{dyn}}} \approx 3 \times 10^{44} \left( \frac{M_{\text{DOM}}}{0.04 \, M_\odot} \right)^{\frac{1}{2}} \left( \frac{v_{\text{ej}}}{15000 \, \text{km s}^{-1}} \right)^{\frac{1}{2}} \left( \frac{v_{\text{ej}} - v_{\text{DOM}}}{2v_{\text{DOM}}} \right)^{\frac{1}{2}} \left( \frac{\kappa}{\kappa_T} \right)^{-\frac{1}{2}} \text{erg s}^{-1}, \quad (12)$$
which is independent of the delay time between DOM formation and explosion, under the simplifying assumptions taken here, as long as $\Delta t_{\text{exp}} < 10^5$ s. This gives a luminosity of $L \sim 10^{44}$ erg s$^{-1}$ from the collision of SN ejecta with the material expelled during the viscous phase. We note that since the value $v_{\text{ej}} = 15000$ km s$^{-1}$ was chosen as a minimal velocity for the outer part of the ejecta which shocks the DOM, the luminosity obtained by using a more detailed ejecta profile might be larger. The effective temperature is

$$T_{\text{eff}} \approx 3 \times 10^5 \left( \frac{M_{\text{DOM}}}{0.04 M_{\odot}} \right)^{\frac{1}{8}} \left( \frac{\Delta t_{\text{exp}}}{10^4 \text{ s}} \right)^{-\frac{1}{2}} \left( \frac{v_{\text{ej}}}{15000 \text{ km s}^{-1}} \right)^{-\frac{1}{2}} \left( \frac{v_{\text{DOM}}}{5000 \text{ km s}^{-1}} \right)^{\frac{1}{2}} \left( \frac{\kappa}{\kappa_T} \right)^{-\frac{1}{8}} \text{K},$$

(13)

which is a UV transient lasting for a few hours, well before the supernova’s peak luminosity at about 20 days. Only $\sim 10^{-5}$ of the radiation is in the visible range, amounting to only $L_V \sim 2 \times 10^{40}$ erg s$^{-1}$.

The derivation above assumed our wind-blown DOM model as summarized in column E of Table 1. If instead we use the DOM scenario of Zhu et al. (2013) described in section 2 (column B of Table 1), we find that the smaller radius of this DOM leads to a shorter dynamical time, $\sim 400$ s. The higher density also means a smaller part of the shocked DOM contributes to the diffused energy, so that the total diffused energy is smaller, $E \sim 10^{48}$ erg. The luminosity, however, is larger than our DOM model, $L \sim 2.5 \times 10^{45}$ erg s$^{-1}$, because of the shorter dynamical time. Since the radius of the shocked DOM is smaller the effective temperature is higher and the diffusion of the shock energy is seen as an X-ray transient lasting for several minutes rather than a longer UV transient as described above.

5. DISCUSSION AND SUMMARY

We have studied some implications of mass ejection during the merger process in the double-degenerate (DD) scenario for SN Ia. As the two WDs merge, the lighter one is destroyed and forms an accretion disk around the more massive WD. Angular momentum and energy must be removed from the merger remnant during the accretion process of the merger. The accretion disk exists for hours (its viscous time), and is expected to blow a wind and/or launch jets that carry away energy and angular momentum. In some models, the gas of the destroyed WD is instead inflated to a large envelope around the massive WD. Some possibilities for the evolution of the merger during the viscous phase are listed in Table 1. Column E is our proposed outflow structure. The matter that is expelled by the disk is termed disk-originated matter (DOM).

In section 3 we assumed that the DOM is expelled spherically. This of course is not the case, but is adequate for our approximate derivation. The typical size and density in the DOM under two
sets of assumptions, summarized in columns B and E of table 1, are given in section 3.

As the merger remnant explodes, the ejecta from the explosion shock the DOM, and kinetic energy is transferred to thermal energy. In section 4, we studied two consequences of this interaction if explosion occurs within about a day from merger. In section 4.1, we concluded that such an interaction will lead to an inferred progenitor radius of \( \gtrsim 0.1 R_\odot \). This is in contradiction with the smaller progenitor radius inferred for SN 2011fe (Nugent et al. 2011; Bloom et al. 2012; Piro & Nakar 2014). In section 4.2, we study the transient signal emerging from this interaction, and find it to be a UV transient lasting up to a few hours.

If the explosion occurs before the complete destruction of the lighter WD, our calculations are not applicable. In that case the explosion will be highly non-spherical (Pakmor et al. 2012b; Moll et al. 2014), which contradicts the morphology of close (Galactic and in the Magellanic Clouds) young SN remnants. The implications at different times of explosion since merger are summarized in Table 2. This study focused on an explosion during the viscous timescale of the accretion disk around the massive WD, \( t_{\text{visc}} \approx 10^3 - 10^5 \) s. If the time delay to explosion is crudely 1–20 days, we expect a strong optical extra peak before the maximum luminosity, when the ejecta catch up to the DOM. If the delay is greater, up to tens of years, a late peak might occur. Delays of over tens of years might not have a prominent observational signature from collision with the DOM, but require a delay mechanism, such as rotation (e.g., Piersanti et al. 2013).

To summarize, our results put a stringent constraint on the DD scenario and limit the possible explosion time after merger to be at least one day after merger, when the temperature of the accreted gas has dropped beneath the requirements for carbon-ignition.

ACKNOWLEDGEMENTS

This research was supported by the Asher Fund for Space Research at the Technion, and the US-Isreal Binational Science Foundation. This work was also partially supported by MCINN grant AYA2011 23102, and by the European Union FEDER funds.

REFERENCES

Aznar-Siguán, G., García-Berro, E., Lorén-Aguilar, P., José, J., & Isern, J. 2013, MNRAS, 434, 2539
Badenes, C., & Maoz, D. 2012, ApJ, 749, L11
Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214
Beloborodov, A. M. 2013, MNRAS, 2926
Bloom, J. S., Kasen, D., Shen, K. J., et al. 2012, ApJ, 744, L17
Pakmor, R., Kromer, M., Taubenberger, S., & Springel, V. 2013, ApJ, 770, L8
Papish, O., Soker, N., García-Berro, E., & Aznar-Siguán, G., submitted
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
Piro, A. L., & Nakar, E. 2014, ApJ, 784, 85
Prodan, S., Murray, N., & Thompson, T. A. 2013,[arXiv:1305.2191]
Raskin, C., Scannapieco, E., Fryer, C., Rockefeller, G., & Timmes, F. X. 2012, ApJ, 746, 62
Raskin, C., & Kasen, D. 2013, ApJ, 772, 1
Schwab, J., Shen, K. J., Quataert, E., Dan, M., & Rosswog, S. 2012, MNRAS, 427, 190
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shen, K. J., Bildsten, L., Kasen, D., & Quataert, E. 2012, ApJ, 748, 35
Shen, K. J., Guillochon, J., & Foley, R. J. 2013, ApJ, 770, L35
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
Ruiter, A. J., Belczynski, K., Sim, S. A., Hillebrandt, W., Fryer, C. L., Fink, M., & Kromer, M. 2011, MNRAS, 417, 408
Thompson, T. A. 2011, ApJ, 741, 82
Tornambé, A., & Piersanti, L. 2013, MNRAS, 431, 1812
Tsebrenko, D., & Soker, N. 2013, MNRAS, 435, 320
Tsebrenko, D., & Soker, N. 2014, submitted[arXiv:1407.6231]
Tutukov, A. V., & Yungelson, L. R. 1979, Acta Astron., 29, 665
van Kerkwijk, M. H., Chang, P., & Justham, S. 2010, ApJ, 722, L157
Webbink, R. F. 1984, ApJ, 277, 355
Whelan, J., & Iben, I., Jr. 1973, ApJ, 186, 1007
Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371
Yoon, S.-C., Podsadlowski, P., & Rosswog, S. 2007, MNRAS, 380, 933
Zhu, C., Chang, P., van Kerkwijk, M. H., & Wadsley, J. 2013, ApJ, 767, 164

This preprint was prepared with the AAS LaTeX macros v5.2.
Table 2. Observational effects of the DD scenario with different explosion times

| $\Delta t_{\text{exp}}$ | Model and Outcome | Observations |
|--------------------------|-------------------|--------------|
| $< t_{\text{visc}}$    | Asymmetrical explosion | Symmetric SNRs |
| $\sim t_{\text{visc}} \lesssim 1\text{ day}$ | Inferred $R_{\text{exp}} > 0.1 \, R_\odot$ | SN 2011fe with $R_{\text{exp}} \lesssim 0.1 \, R_\odot$ |
| $\sim 1 - 20 \text{ days}$ | Extra radiation, possible peak before maximum | Not observed |
| $\sim 20 \text{ days} - 10 \text{ yr}$ | Late peak | Not observed |
| $\gg 10 \text{ yr}$ | No effect, but this requires an explosion delay mechanism | - |

Note. — $t_{\text{visc}} \sim 10^3 - 10^4 \, s$ is the viscous time.

$t_{\text{max}} \simeq 20 \text{ days}$ is the time to maximum light.