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

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ABSTRACT
We follow the mass expelled during the WD-WD merger process in a particular case of the Double-Degenerate (DD) scenario for Type Ia supernovae (SNe Ia), and find that the interaction of the SN ejecta with the resulting wind affects the early (first day) light curve in a way that may be in conflict with some SN Ia observations, if the detonation occurs shortly after the merger (i.e., $10^3\ \mathrm{sec} \lesssim t_{\rm exp} \lesssim 1\ \mathrm{day}$). The main source of the expelled mass is a disk-wind, or jets that are launched by the accretion disk around the more massive WD during the viscous phase of the merger. This disk-originated matter (DOM) will be shocked and heated by the SN ejecta from an explosion, leading to additional radiation in the early lightcurve. This enhanced early radiation could then be interpreted as an explosion originating from a progenitor having an inferred radius of one solar radius or more, in conflict with observations of SN 2011fe.

Key words: accretion, accretion disks – binaries: close – hydrodynamics – supernovae: general – white dwarfs

1 INTRODUCTION

There is no consensus on the evolutionary routes that bring CO white dwarfs (WDs) in binary systems to explode as Type Ia supernovae (SNe Ia; e.g., Livio 2001; Maoz 2010; Howell 2011; Maoz et al. 2014; Ruiz-Lapuente 2014; Tsebrenko & Soker 2015b). The different scenarios currently considered can be summarized as follows (for more details and a table comparing the pros and cons of the five scenarios see Tsebrenko & Soker 2015b).
(a) *The double degenerate (DD) scenario* (e.g., Webbink 1984; Iben & Tutukov 1984). In this scenario two WDs orbiting each other lose angular momentum and energy through the radiation of gravitational waves (Tutukov & Yungelson 1979), and a merger occurs. 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 mass explosions as well (e.g., van Kerkwijk et al. 2010; Badenes & Maoz 2012). In recent years a violent merger process was proposed as a channel to ignite the WD (e.g., Lorén-Aguilar et al. 2010; Pakmor et al. 2013). Others consider a very long delay from merger to explosion, e.g., because rapid rotation keeps the structure stable even as the accreting remnant exceeds the Chandrasekhar mass ($M_{\rm Ch}$; Tornambé & Piersanti 2013).
(b) *The core-degenerate (CD) scenario* (Sparks & Stecher 1974; 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 (CE) phase, hence leading to a SN Ia inside a planetary nebula (Tsebrenko & Soker 2013, 2015a,b), or after a very long time delay. There is some overlap between the DD and CD scenarios, in the sense that if the merger occurs after the termination of the CE phase, but while the core is not yet on the cooling track of a WD, both scenarios describe the same system. Basically, this occurs when the merger occurs during the planetary nebula phase of the system.
(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, and explodes as it approaches the Chandrasekhar mass. 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; Piersanti et al. 2014 for recent papers). While Ruiter et al. (2011) found that a large fraction of SN Ia can be attributed to the sub-Chandrasekhar DDet scenario, Piersanti et al. (2013) found that the DDet scenario

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can account for only a small fraction of all SN Ia. More recently Ruiter et al. (2014) argued that the DDet scenario can account for a large fraction of SN Ia if most ($> 70\%$) of the donors are He WDs. Papish et al. (2015) found that the explosion in the case of a He WD donor leads to a non-spherical SN remnant (SNR), and in the case of a close helium WD, the latter will be ignited and will eject too much helium to be compatible with observations. Papish et al. (2015) also pointed out that the expected SNR has a dipole asymmetry that no well-resolved SNR Ia has. Another issue with this scenario is that because the exploding CO WD barely grows before it explodes (Shen & Bildsten 2009), the DDet scenario predicts that most exploding WDs will have a mass of $< 1.2\,\mathrm{M}_{\odot}$. This is at odds with recent findings that a large fraction of SN Ia masses are peaked around $1.4\,\mathrm{M}_{\odot}$ (Scalzo et al. 2014). Seitenzahl et al. (2013) also claim that at least 50% of all SN Ia come from near-Chandrasekhar mass WDs. It seems that the DDet scenario can lead to explosions similar to SN Ia, but not to common SN Ia.

(e) *The WD-WD collision scenario.* In this scenario two WDs collide directly, either because of interaction with a tertiary star (e.g., Thompson 2011; Katz & Dong 2012; Kushnir et al. 2013), or by random encounters in dense stellar systems such as globular clusters (e.g., Raskin et al. 2009; Rosswog et al. 2009; Aznar-Siguán et al. 2013). 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 tables of Soker et al. (2014) and Tsebrenko & Soker (2015b), 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 DD scenario, postponing the CD scenario to a future paper.

The paper is organized as follows. 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; Zhu et al. 2013) have used smoothed particle hydrodynamics (SPH) simulations to evolve a binary WD system from first contact until the complete destruction of the donor. This is referred to as the dynamical phase of the merger. Some of these simulations are summarized in Table 1. While different initial conditions are used in these simulations, most results are common to all them. After a time $t_{\rm dyn} \sim 100$ s that corresponds to several orbital periods, the donor is completely disrupted. The merged product consists of the more massive primary WD, which remains almost intact, with the material of the donor residing in a hot corona surrounding it and in a nearly Keplerian disk extending out to $\sim 0.1\,\mathrm{R}_{\odot}$. In addition, a tidal tail with a mass of $\sim 10^{-3}\,\mathrm{M}_{\odot}$ is unbound from the system (e.g. Raskin & Kasen 2013). A different possibility is the violent merger scenario of Pakmor et al. (2012b). They found that in some dynamical mergers hot spots are formed, which experience a thermonuclear runaway. The resulting explosion is highly asymmetrical Pakmor et al. (2012b). However, such asymmetrical explosions are in contradiction with some resolved SNR in the Galaxy and the Magellanic clouds (Lopez et al. 2011; see more in section 5). 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.

An important property of systems following a dynamical merger is a clear hierarchy of timescales. The dynamical timescale of the merger $t_{\rm dyn} \sim \Omega^{-1}$ is of the order of seconds. Next in 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 is usually done using the Shakura-Sunyaev α-prescription (Shakura & Sunyaev 1973), giving a timescale of $t_{\rm visc} \sim \alpha^{-1} \left(R_{\rm disk}/H\right) t_{\rm dyn}$ with $R_{\rm disk}$, H and $t_{\rm dyn}$ the disk radius, scale height and dynamical timescale, respectively (e.g. van Kerkwijk et al. 2010). Taking a suitable value of $\alpha = 0.01 - 0.1$ gives a viscous timescale of $t_{\rm visc} \sim 10^3 - 10^4$ 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 $t_{\rm dyn} \ll t_{\rm visc} \ll t_{\rm th}$ 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 the merger and the explosion is very long, up to millions of years, as expected if rotation keeps the remnant stable even when it exceeds $M_{\rm Ch}$ (e.g.,Tornambé & Piersanti 2013).

Schwab et al. (2012) and Zhu et al. (2013) investigated the evolution of the merger product following the dynamical phase. Of the various systems studied by Schwab et al. (2012), none developed a thermonuclear runaway. Zhu et al. (2013) evolved the remnant of a $0.8\,\mathrm{M}_{\odot} + 0.4\,\mathrm{M}_{\odot}$ fiducial system, and found that a mass of $0.25\,\mathrm{M}_{\odot}$ was expelled – a value much higher than for similar systems in Schwab et al. (2012). If the assumptions of Zhu et al. (2013) are accepted, the removed mass is the matter that is not accreted due to angular momentum conservation. This matter is marginally unbound, and can correspond to the giant structure of Schwab et al. (2012), which is not unbound but is significantly extended around the degenerate merger.

Severe constraints have already been placed on the DD scenario as a frequent channel for typical SNIa explosions by the above mentioned studies, as well as by other studies. The companion papers of Moll et al. (2014) and Raskin et al. (2013) stress the large variations in viewing angle for an explosion during or directly after the dynamical merger, respectively. Raskin et al. (2013) also show that an explosion inside the accretion disk leads to excessive ^{56}Ni production and peculiar observables for merger products with a total mass exceeding the Chandrasekhar mass, while Schwab et al. (2012) show that less massive merger products fail to explode. The failure to detonate could mean that the remnant eventually collapses to a neutron star (Saio & Nomoto 1985). However, since other studies do support the possibility of the DD scenario leading to standard SNIa explosions (e.g., van Kerkwijk et al. 2010; Zhu et al. 2013), it seems plausible to further address the implications of matter launched by winds or jets during the viscous phase, on an explosion at a somewhat later time, when the disk matter has been accreted or

Table 1. Comparison of outcomes of the DD scenario.

Papers	Shen et al. (2012); Schwab et al. (2012)	van Kerkwijk et al. (2010); Zhu et al. (2013)	Ji et al. (2013); Zhu et al. (2013)	Pakmor et al. (2012b)	This paper
Fiducial system ($M_\odot$)	$0.9 + 0.6$	$0.8 + 0.4$ or $0.6 + 0.6$	$0.6 + 0.6$	$1.2 + 0.9$	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 $v_{\rm esc}\left(R_{\rm rem}\right)$
$t_{\rm acc}$ (s)	3×10^4	N/A	2×10^4	N/A	$\sim 10^4$
Remnant star[1]					
$M_{\rm rem}$ ($M_\odot$)	1.04	0.96 or 0.91	1.12	2	$\sim 1 - 1.5$
$R_{\rm rem}$ ($R_\odot$)	0.007	0.01 or 0.02	0.03	0.03	$\lesssim 0.02$
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[2]					
$M_{\rm env}$ ($M_\odot$)	0.46	N/A	0.06	N/A	N/A
$R_{\rm env}$ ($R_\odot$)	1.4	N/A	0.14	N/A	N/A
Disk-Wind (DOM)[3]					
$M_{\rm DOM}$ ($M_\odot$)	6×10^{-6}	0.25; 0.29	10^{-3}	5×10^{-3}	0.04
$v_{\rm DOM}$ (km s^{-1})	N/A	~ 2000 [4]	~ 3000	~ 2000	~ 5000 [5]
Comments		Optically thick DOM at $\sim 1 - 10\ R_\odot$ contradicts SN 2011fe (Bloom et al. 2012; Piro & Nakar 2014)	Jets were proposed for Kepler SNR (Tsebrenko & Soker 2013); DOM is expected	Highly asymmetrical explosion contradicts resolved Type Ia SNR (Lopez et al. 2011)	Such an outflow contradicts SN 2011fe (see Section 4)

Notes:
AM = angular momentum.
$v_{\rm esc}$ is the escape velocity from the remnant during the accretion phase $v_{\rm esc} = \sqrt{2GM_{\rm rem}/R_{\rm rem}}$.
[1]The primary with the accreted mass from the disk (not the SNR).
[2]At the time of explosion $t = 610$ s in Pakmor et al. (2012b) a dense gas from the destroyed WD extends up to distances of $\sim 0.015 - 0.03\ R_\odot$, and more rarefied gas (seen at $t = 612$ s in their figure 1) extends up to $\sim 0.03 - 0.045\ R_\odot$. We therefore mark the typical radius of the remnant in their simulation as $0.03\ R_\odot$.
[3]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.
[4]Material is ejected with zero total energy. $v_{\rm DOM} = v_{\rm esc}\left(R_{\rm DOM}\right)$.
[5]Material is ejected with a terminal velocity of $v_{\rm DOM} = v_{\rm esc}\left(R_{\rm rem}\right)$.

expelled. Since it is focused on this later time period, our study can be viewed as complementary to studies of the observational properties of an explosion during or directly after the dynamical merger (Moll et al. 2014; Raskin et al. 2013).

In the studies mentioned above, a common feature 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 $> 1\ R_\odot$ (e.g. last panel of their Fig. 5). 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 SN Ia, whose size is an order of magnitude smaller, e.g. SN 2011fe (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

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

where $R_{\rm rem}$ 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

$$R_{\rm DOM} \simeq v_{\rm DOM} t = 72 \left(\frac{v_{\rm DOM}}{5000~{\rm km~s^{-1}}} \right) \left(\frac{t}{10^4~{\rm s}} \right) ~{\rm R_\odot}. \quad (2)$$

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

$$\bar\rho_{\rm DOM} \simeq 1.5 \times 10^{-7} \left(\frac{M_{\rm DOM}}{0.04~{\rm M_\odot}} \right) \times \left(\frac{v_{\rm DOM}}{5000~{\rm km~s^{-1}}} \right)^{-3} \left(\frac{t}{10^4~{\rm s}} \right)^{-3} ~{\rm g~cm^{-3}}, \quad (3)$$

where $M_{\rm DOM}$ 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 $0.4-0.8~{\rm M_\odot}$. Taking free electron scattering opacity ($\kappa_{\rm T} = 0.2~{\rm cm^2~g^{-1}}$) as a lower bound, the optical depth is

$$\tau \gtrsim \kappa_{\rm T} \bar\rho_{\rm DOM} r_{\rm DOM} = 1.5 \times 10^5 \left(\frac{M_{\rm DOM}}{0.04~{\rm M_\odot}} \right) \times \left(\frac{v_{\rm DOM}}{5000~{\rm km~s^{-1}}} \right)^{-2} \left(\frac{t}{10^4~{\rm s}} \right)^{-2} \left(\frac{\kappa}{\kappa_{\rm T}} \right). \quad (4)$$

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 $\gtrsim 1~{\rm R_\odot}$, in contradiction with SN 2011fe whose progenitor radius is limited to $R \lesssim 0.1~{\rm R_\odot}$ (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 ($\sim 10^{-3}~{\rm M_\odot}$) 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 $v_{\rm esc} = \sqrt{2GM_{\rm rem}/R_{\rm DOM}}$, where $M_{\rm rem}$ is the remnant mass. The mass of the DOM is also larger, $\sim 0.2~{\rm M_\odot}$. This leads to a more compact DOM, of radius

$$R_{\rm DOM} \simeq \left(\frac{3}{2} \sqrt{2GM_{\rm rem}} \cdot t + R_0^{\frac{3}{2}} \right)^{\frac{2}{3}} \sim 5.6 \left(\frac{M_{\rm rem}}{1~{\rm M_\odot}} \right)^{\frac{1}{3}} \left(\frac{t}{2 \times 10^4~{\rm s}} \right)^{\frac{2}{3}} ~{\rm R_\odot}, \quad (5)$$

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 $1~{\rm R_\odot}$ the thermal energy is reduced to ~ 0.02 times its initial value for an initial WD radius of $R_{\rm WD} = 0.02~{\rm R_\odot}$. In our model the DOM, with a mass of $M_{\rm DOM} \sim 0.04~{\rm M_\odot}$, is shocked at $R_{\rm DOM} \sim 10-100~{\rm R_\odot}$. The relative velocity between the DOM, with $v_{\rm DOM} \lesssim 5000~{\rm km~s^{-1}}$, and the ejecta, with $v_{\rm ej} \sim 15,000~{\rm km~s^{-1}}$, implies that the amount of kinetic energy that is transferred to thermal energy during the collision is $E_{\rm shock} \simeq 5 \times 10^{50} (M_{\rm DOM}/M_\odot)$ erg. This can be much larger than the thermal energy of the ejecta just before it hits the DOM, $\simeq 5 \times 10^{50} (R_{\rm prog}/R_{\rm DOM})$ erg, where $R_{\rm prog}$ 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}Ni decay becomes dominant (e.g., Nugent et al. 2011), the observations will be interpreted as if the progenitor radius was

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

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 $R_{\rm WD} \lesssim 0.1~{\rm R_\odot}$ limits the DOM mass at $R_{\rm DOM} \sim 100~{\rm R_\odot}$ to $\lesssim 10^{-3}~{\rm M_\odot}$. Note that using the more massive and compact DOM derived from the Zhu et al. (2013) fiducial model gives an inferred progenitor radius, $R_{\rm prog,i} \simeq 0.7~{\rm R_\odot}$, 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 $\sim 20,000~{\rm km~s^{-1}}$. 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 $M_{\rm DOM} \sim 0.04~{\rm M_\odot}$. This gives $v_{\rm ej} \simeq 15,000~{\rm km~s^{-1}}$. The shock passes through the DOM in a dynamical time

$$t_{\rm dyn} \simeq 5 \times 10^3 \left(\frac{v_{\rm ej} - v_{\rm DOM}}{2 v_{\rm DOM}} \right)^{-1} \left(\frac{\Delta t_{\rm exp}}{10^4~{\rm s}} \right) ~{\rm s}, \quad (7)$$

where $\Delta t_{\rm exp}$ 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 $t_{\rm dyn}$ will escape. More photons

Table 2. Observational effects of the DD scenario with different explosion times.

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

Notes:
$t_{\rm visc} \sim 10^3 - 10^4$ s is the viscous time.
$t_{\rm max} \simeq 20$ days is the time to maximum light.

will diffuse later, and lead to the inferred large progenitor radius as discussed in section 4.1. The diffusion time is given by

$$t_{\rm dif} = \tau \frac{l_{\rm dif}}{3c} = \frac{l_{\rm dif}^2 \kappa \rho_{\rm s}}{3c} \quad (8)$$

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

$$l_{\rm dif} \sim 1.2 \left(\frac{M_{\rm DOM}}{0.04~{\rm M}_{\odot}}\right)^{-\frac{1}{2}} \left(\frac{\Delta t_{\rm exp}}{10^4~{\rm s}}\right)^{2} \left(\frac{v_{\rm ej}}{15000~{\rm km~s^{-1}}}\right)^{\frac{3}{2}} \times \left(\frac{v_{\rm ej} - v_{\rm DOM}}{2 v_{\rm DOM}}\right)^{-2} \left(\frac{\kappa}{\kappa_{\rm T}}\right)^{-\frac{1}{2}} {\rm R}_{\odot}. \quad (9)$$

The diffusion distance cannot be larger than the length of the shocked DOM, which is approximately $l_{\rm DOM,shocked} \sim 0.1 R_{\rm DOM}$. The last equation and the following ones assume that indeed $l_{\rm dif} \leqslant l_{\rm DOM,shocked}$, which is valid therefore for $\Delta t_{\rm exp} \lesssim 10^5$ s. For a larger $\Delta t_{\rm exp}$, instead of equation (9) we have $l_{\rm dif} \simeq l_{\rm DOM,shocked}$. The energy density in the diffusion volume is $\epsilon_{\rm s} = 3p_{\rm s}$. 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,

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

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

$$\begin{aligned} E \approx & 0.5 \cdot 0.5 \cdot 3p_{\rm s} \cdot 4\pi R_{\rm DOM}^2 l_{\rm dif} \\ \simeq & 1.7 \times 10^{48} \left(\frac{M_{\rm DOM}}{0.04~{\rm M}_{\odot}}\right)^{\frac{1}{2}} \left(\frac{\Delta t_{\rm exp}}{10^4~{\rm s}}\right) \left(\frac{v_{\rm ej}}{15000~{\rm km~s^{-1}}}\right)^{\frac{1}{2}} \times \\ & \left(\frac{v_{\rm DOM}}{5000~{\rm km~s^{-1}}}\right) \left(\frac{v_{\rm ej} - v_{\rm DOM}}{10000~{\rm km~s^{-1}}}\right) \left(\frac{\kappa}{\kappa_{\rm T}}\right)^{-\frac{1}{2}} {\rm erg}, \quad (11) \end{aligned}$$

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 $t_{\rm dyn}$ is

$$L \approx \frac{E}{t_{\rm dyn}} \simeq 3 \times 10^{44} \left(\frac{M_{\rm DOM}}{0.04~{\rm M}_{\odot}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm ej}}{15000~{\rm km~s^{-1}}}\right)^{\frac{1}{2}} \times \left(\frac{v_{\rm ej} - v_{\rm DOM}}{10000~{\rm km~s^{-1}}}\right)^{2} \left(\frac{\kappa}{\kappa_{\rm T}}\right)^{-\frac{1}{2}} {\rm erg~s^{-1}}, \quad (12)$$

which is independent of the delay time between DOM formation and explosion, under the simplifying assumptions taken here, as long as $\Delta t_{\rm exp} < 10^5$ s. This gives a luminosity of $L \sim 10^{44}~{\rm erg~s^{-1}}$ from the collision of SN ejecta with the material expelled during the viscous phase. We note that since the value $v_{\rm ej} = 15000~{\rm km~s^{-1}}$ 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

$$T_{\rm eff} \approx 3 \times 10^{5} \left(\frac{M_{\rm DOM}}{0.04~{\rm M}_{\odot}}\right)^{\frac{1}{8}} \left(\frac{\Delta t_{\rm exp}}{10^4~{\rm s}}\right)^{-\frac{1}{2}} \times \left(\frac{v_{\rm ej}}{15000~{\rm km~s^{-1}}}\right)^{-\frac{3}{8}} \left(\frac{v_{\rm DOM}}{5000~{\rm km~s^{-1}}}\right)^{\frac{1}{2}} \left(\frac{\kappa}{\kappa_{\rm T}}\right)^{-\frac{1}{8}} {\rm K}, \quad (13)$$

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 $L_{\rm V} \sim 2 \times 10^{40}~{\rm erg~s^{-1}}$.

Using high cadence observations, Siverd et al. (2014) put an upper limit on any short-term luminosity variations of SN 2014J of $L < 8.7 \times 10^{36}~{\rm erg~s^{-1}}$ in the *R*-band. Using this in equation (12) we can set a limit of $M_{\rm DOM} \lesssim 4 \times 10^{-6}~{\rm M}_{\odot}$ for a velocity difference of only $v_{\rm ej} - v_{\rm DOM} = 1000~{\rm km~s^{-1}}$. This tight limit on DOM mass rules out an accretion event if the explosion occurred more than few minutes after merger. Goobar et al. (2014) show that a model with a large progenitor radius $\gtrsim 1~{\rm R}_{\odot}$ nevertheless fits these observations, when fixing the early lightcurve time dependence according to the fireball model ($L \propto t^2$). A progenitor of $\sim 0.02~{\rm R}_{\odot}$ is also possible when relaxing this constraint, however, and the validity of the t^2 time dependence as a general property of early SN Ia lightcurves is an open question (e.g., Piro & Nakar 2013; Firth et al. 2014). If indeed the progenitor is large, our results indicate that the explosion must take place within few hundreds seconds to comply with the luminosity limit of Siverd et al. (2014).

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, $\sim 400\,\mathrm{s}$. 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, $E \simeq 10^{48}\,\mathrm{erg}$. The luminosity, however, is larger than our DOM model, $L \simeq 2.5 \times 10^{45}\,\mathrm{erg\,s^{-1}}$, 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 SNe Ia, for cases where explosion occurs shortly, but not promptly, after merger, i.e., in the time range $10^3\ \mathrm{s} \lesssim t_{\rm exp} \lesssim 1\ \mathrm{day}$ after merger. 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 $\gtrsim 0.1\ \mathrm{R_\odot}$. 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. We then used the derived luminosity to argue that SN 2014J could not have exploded in the DD scenario if the explosion occurred during the viscous phase. The time of explosion in a DD model for SN 2014J can be further constrained, up to tens of years after merger (see below).

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; Raskin et al. 2013), which contradicts the morphology of some close (Galactic and in the Magellanic Clouds) young SN remnants. We can list several SNR that show no dipole asymmetry (images from the Chandra SNR catalogue [1]; Seward et al. 2004). SNRs that have (almost) spherical morphology include the Tycho SNR and SNR 0509-67.5. The simulations of Papish et al. (2015) suggest that the presence of any companion will lead to large dipole asymmetry, not observed in these SNRs. The SNRs G1.9+0.3 and Kepler have two opposite 'Ears', but don't show a prominent dipole morphology. These also seem not to result from explosions taking place before the complete destruction of the companion WD. One SNR that does show a dipole asymmetry is SN 1006. However, Papish et al. (2015) find this dipole structure to be different from the one expected due to the effect of the He WD companion on the ejecta in the DDet scenario. Further simulations are needed to follow the SNRs that result from explosions taking place before complete donor destruction in the DD scenario. Some SNRs are old and have no well-defined shapes, while in some other SNRs the dipole asymmetry might result from an interaction with the ISM; we do not refer to them here.

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, $t_{\rm visc} \approx 10^3 - 10^5\ \mathrm{s}$. Our study is complementary to those of Moll et al. (2014) and Raskin et al. (2013) who explored the consequences of an explosion during or immediately after the dynamical merger. Put together, the regime they explored and the regime we do in the present study leave a small window for the DD scenario to be compatible with observations of typical SN Ia, unless a much larger time delay until an eventual explosion is considered. If the time delay to explosion is crudely $1 - 20\ \mathrm{days}$, 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., Tornambé & Piersanti 2013). Such a long delay will allow a merger remnant of near-Chandrasekhar mass to develop. An exploding near-Chandrasekhar mass WD is compatible with recent findings that a large fraction of SN Ia masses are peaked around $1.4\ \mathrm{M_\odot}$ (Scalzo et al. 2014), as required also for manganese nucleosynthesis (Seitenzahl et al. 2013).

To summarize, our results put a stringent constraint on the time of explosion of any DD scenario where a violent merger does not occur. For systems where the conditions for explosion are not reached during the dynamical merger, the subsequent creation of an extended structure of DOM via jets or a disk-wind is unavoidable on account of angular momentum conservation. If the explosion is to occur at this stage, the additional radiation from cooling of the gas heated in the ejecta-DOM shock will be observable, and inflate the value of the inferred progenitor radius to $\gtrsim 1\ \mathrm{R_\odot}$. These considerations suggest that possible explosion times after the dynamical merger are at least one day after merger, when the temperature of the accreted gas has dropped beneath the requirements for carbon-ignition. Non-violent DD models which propose an explosion of the merger remnant should therefore contain a suitable delay mechanism.

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[1] http://hea-www.cfa.harvard.edu/ChandraSNR/

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