PREDICTING THE AMOUNT OF HYDROGEN STRIPPED BY THE SN EXPLOSION FOR SN 2002cx-LIKE SNe Ia

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ABSTRACT
The most favored progenitor scenarios for Type Ia supernovae (SNe Ia) involve the single-degenerate (SD) scenario and the double-degenerate scenario. The absence of stripped hydrogen (H) in the nebular spectra of SNe Ia challenges the SD progenitor models. Recently, it was shown that pure deflagration explosion models of Chandrasekhar-mass white dwarfs, ignited off-center, reproduce the characteristic observational features of 2002cx-like SNe Ia very well. In this work we predict, for the first time, the amount of stripped H for the off-center, pure deflagration explosions. We find that their low kinetic energies lead to inefficient H mass stripping ($\lesssim 0.1\, M_\odot$), indicating that the stripped H may be hidden in (observed) late-time spectra of SN 2002cx-like SNe Ia.

Key words: binaries: close – methods: numerical – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are instrumental as distance indicators on a cosmic scale to determine the expansion history of the universe (Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999). They are widely believed to be caused by thermonuclear explosions of carbon/oxygen white dwarfs (C/O WDs) in binary systems. The two favored classes of SN Ia progenitors are the single-degenerate (SD) scenario and double-degenerate (DD) scenario. In the DD scenario, two C/O WDs merge due to gravitational wave radiation, leading to an SN Ia thermonuclear explosion (e.g., Iben & Tutukov 1984). In the SD scenario, WDs accrete H/He-rich matter from companions that could be main-sequence (MS) stars, sub-giants, red giants (RGs), or He stars. They ignite SN Ia explosions when approaching the Chandrasekhar-mass ($M_{\text{Ch}}$) limit (e.g., Whelan & Iben 1973; Hachisu et al. 1996; Han & Podsiadlowski 2004).

Recently, some observational and hydrodynamical studies (see, e.g., Li et al. 2011; Nugent et al. 2011; Chomiuk et al. 2012; Horesh et al. 2012; Bloom et al. 2012; Schaefer & Pagnotta 2012; Pakmor et al. 2010, 2011, 2012b) have supported the viability of the DD scenario. There are some observational indications (see, e.g., Patat et al. 2007; Sternberg et al. 2011; Foley et al. 2012; Dilday et al. 2012) suggesting that the progenitors of some SNe Ia may come from the SD scenario. However, the exact nature of SN Ia progenitors remains uncertain (see Hillebrandt & Niemeyer 2000; Hillebrandt et al. 2013 for reviews).

The spectra of normal SNe Ia are characterized by the absence of H and He lines and a strong silicon absorption feature. To date, no direct observation shows the signature of H lines in late-time, nebular spectra of SNe Ia (Mattila et al. 2005; Leonard 2007; Shappee et al. 2013). One of the signatures of the SD scenario is that the SN Ia explosion is expected to remove H/He-rich material from its non-degenerate companion star (Wheeler et al. 1975). Hydrodynamical simulations with a classical SN Ia explosion model (i.e., the W7 model; see Nomoto et al. 1984) showed that about 0.1 $M_\odot$ H-rich material is expected to be stripped off from an MS companion star by the impact of the SN Ia ejecta (see, e.g., Marietta et al. 2000; Pakmor et al. 2008; Liu et al. 2012, 2013a; Pan et al. 2012). Almost the whole envelope of an RG companion ($\sim 0.5\, M_\odot$) is removed (see, e.g., Marietta et al. 2000; Pan et al. 2012). The amount of stripped H is significantly above the most stringent upper limits on non-detection of H ($\sim 0.01$–$0.03\, M_\odot$; see Leonard 2007; Lundqvist et al. 2013), which were derived from observations of normal SNe Ia. Moreover, Shappee et al. (2013) obtained a lower limit of $\sim 0.001\, M_\odot$ on detection of stripped H for SN 2011fe, which is the nearest SN Ia in the past 25 years and has been observed in unprecedented detail. Therefore, the absence of He in late-time nebular spectra of SNe Ia poses some problems for the SD scenario and favors other progenitor channels such as a WD merger (see Pakmor et al. 2010, 2011, 2012b). However, all previous hydrodynamical simulations were performed with the classical W7 explosion model, which is suitable for normal SNe Ia in nickel production and kinetic energy.

SN 2002cx-like SNe are spectroscopically peculiar and faint objects compared to other SNe Ia. Their spectra are characterized by very low expansion velocities and show strong mixing of the explosion ejecta (Jha et al. 2006; Phillips et al. 2007). Moreover, SN 2002cx-like SNe are proposed to originate from Chandrasekhar-mass deflagrations, i.e., SD H-accreting progenitors. Very recently, Kromer et al. (2013) performed hydrodynamics (see also Jordan et al. 2012) and radiative-transfer calculations for a three-dimensional (3D) full-star pure deflagration model (i.e., the NSdef model; see Fink et al. 2013), which is able to reproduce the characteristic observational features of SN 2005hk (a prototypical 2002cx-like SN Ia). In the NSdef model, only a part of the $M_{\text{Ch}}$ WD, $\sim 0.37\, M_\odot$, is ejected, with a much lower kinetic energy ($\sim 1.34 \times 10^{50}\, \text{erg}$) than models for normal SNe Ia. The thermonuclear explosion fails to completely unbind the WD and leaves behind a bound remnant of $\sim 1.03\, M_\odot$ that consists mainly of unburned C/O (see Jordan et al. 2012; Kromer et al. 2013;...
Fink et al. 2013). The small amount of kinetic energy released in this pure deflagration model might significantly decrease the stripped companion mass, potentially avoiding a signature of H lines in late-time spectra of SN 2002cx-like SNe Ia.

Here we calculate the amount of stripped H for the N5def model (which is the best current model for SN 2002cx-like SNe Ia) in the SD scenario using 3D hydrodynamical simulations of the impact of the SN ejecta on MS companion stars. The paper is organized as follows. In Section 2, we describe the methods and codes used in this work. Section 3 presents the results from hydrodynamical simulations. The distribution of the unbound mass from population synthesis calculations is shown in Section 4. Discussions based on the results of impact simulations are presented in Section 5. Finally, we summarize the basic results of simulations in Section 6.

2. NUMERICAL METHOD AND MODEL

In order to construct a detailed companion structure at the moment of the SN Ia explosion, we used the same method as described in Liu et al. (2012) to trace a binary evolution in which a WD accretes H-rich material from an MS companion star (i.e., WD+MS MCh explosion scenario). We think that the WD would explode as an SN Ia when its mass increases to the MCh limit. Here, we adopted the Eggleton stellar evolution code, including Roche-lobe overflow and the optically thick wind model of Hachisu et al. (1996) in the code to treat mass transfer in the binary. With a series of consistent binary evolution calculations, we selected four companion star models as input models of hydrodynamical simulations. These four companion stars were constructed with different initial WD masses, companion masses, and orbital periods (see Table 1), which lead to companion models different in mass, orbital period, and detailed structure at the moment of the SN explosion. Four companion models created in 1D binary evolution calculations are summarized in Table 1, and their radial mass profiles are shown in Figure 1. We then performed 3D hydrodynamical simulations of the impact of SN Ia ejecta on the companion star employing the SPH code Stellar GADGET (Pakmor et al. 2012a; Springel 2005).

In this work, all initial conditions and basic setup for the impact simulations are the same as those in Liu et al. (2012). We use the healpix method described in Pakmor et al. (2012a) to map the 1D profiles of density and internal energy of a 1D companion star model to a particle distribution suitable for the SPH code. Before we start the actual impact simulations, the SPH model of each companion star is relaxed for several dynamical timescales to reduce numerical noise introduced by the mapping. A comparison of density profiles between the 1D stellar model and its consistent SPH model for Model_A is shown in Figure 2.

The SN Ia explosion was represented by the pure deflagration model of Kromer et al. (2013) (i.e., the N5def model). This model has been shown to reproduce the characteristic observational features of 2002cx-like SNe Ia well (Kromer et al. 2013). In this simulation, only the 0.37 M⊙ of ejected material with a total kinetic energy of \(1.34 \times 10^{50}\) erg were used to represent the SN Ia explosion. We did not include the 1.03 M⊙ bound remnant of the MCh WD in the simulations. Based on the angle-averaged 1D ejecta structure of the N5def model, SPH particles were placed randomly in shells to reproduce the mass (density) profile and gain the radial velocities they should have at their positions. The composition of a particle was then set to the

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**Table 1**

| Model | MWD (M⊙) | M2f (M⊙) | R2f (10^13 cm) | aR | ΔMDf (M⊙) | ΔMW7f (M⊙) | vkick_W7 (km s⁻¹) | Def_vkick_W7 (km s⁻¹) |
|-------|-----------|-----------|----------------|----|------------|-------------|-----------------|----------------------|
| Model_A | 0.8 | 2.2 | 1.21 | 0.65 | 1.77 | 0.015 | 0.173 | 24.4 | 105.3 |
| Model_B | 0.9 | 2.4 | 1.40 | 0.74 | 1.95 | 0.016 | 0.172 | 22.8 | 94.9 |
| Model_C | 1.0 | 2.4 | 1.88 | 0.91 | 2.25 | 0.013 | 0.116 | 15.9 | 66.9 |
| Model_D | 1.2 | 3.0 | 2.45 | 1.13 | 2.64 | 0.016 | 0.172 | 22.8 | 94.9 |

Notes. MWD and M2f present the WD and companion mass at the beginning of mass transfer. M2f, R2f, and aR demonstrate the companion mass, companion radius, and binary separation at the time of the explosion. ΔMDf and ΔMW7f show the unbound companion masses in the impact simulations for the pure deflagration model and the W7 model. vkick_W7 and Def_vkick correspond to the companion kick velocities.

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**Figure 1.** Mass vs. radius profiles for four main-sequence companion models used in the impact simulations.

**Figure 2.** Radial profiles of the density for a 1D companion model (i.e., Model_A) and its corresponding 3D SPH model generated by the healpix method (see Pakmor et al. 2012a).

(A color version of this figure is available in the online journal.)
values of the initial 1D model at a radius equal to the radial coordinate of the particle. Here, we ignored the effect of a mild degree of asymmetry caused by an off-center, pure deflagration explosion of an $M_{\text{Ch}}$ WD. However, only in the direction opposite to the one-sided ignition region are the velocities somewhat lower (Fink et al. 2013) and the asymmetries of the ejecta reduced due to the strong expansion. The orientation of an asymmetry of SN ejecta plays an inefficient role in mass stripping by the time of interaction with the companion.7

We used $6 \times 10^6$ million SPH particles to represent the He companion stars in all simulations of this work.8 Because all SPH particles were set up with the same mass, the number of particles representing the SN explosion is then fixed. The SN was placed at a distance to the companion star given by the separation at the moment of SN Ia explosion in our 1D binary-evolution calculations. The impact of the SN Ia ejecta on their binary companions was then simulated for 5000 s, at which point the mass stripped off from the companion star and its kick velocity due to the impact have reached constant values.

3. HYDRODYNAMICAL RESULTS

Figure 3 shows the typical evolution of the density distribution in the impact simulations for the companion star Model_A. Compared to our previous hydrodynamical simulations for the same MS companion star model (but with a different explosion model; see Liu et al. 2012), the basic impact processes are quite similar. The SN explodes at the right side of the companion star. After the SN explosion, the SN ejecta expand freely for a while and hit the MS companion star, removing solar-metallicity companion material and forming a bow shock. Subsequently, the bow shock propagates through the companion star, causing an additional loss of H-rich companion material from the far side of the star. Finally, the final unbound H-rich material of the companion star caused by the SN impact is largely embedded in low-velocity SN debris behind the companion star, and the strongly impacted companion starts to relax and become almost spherical again.

After the SN explosion, the non-degenerate companion star is significantly hit by the SN ejecta. The SN impact removes H-rich material from outer layers of the companion star through the ablation (SN heating) and the stripping (momentum transfer) mechanism. The late-time spectra of SNe Ia probably show a signature of H lines if a large amount of H-rich material can be stripped from the companion star during the interaction with the SN ejecta. To calculate the amount of final unbound companion mass due to the SN impact, we sum the masses of all unbound SPH particles (ablated+stripped particles) that originally belong to the companion star at the end of the simulations.

For four different MS companion star models, our impact simulations show that the companion star received a kick velocity of $\sim$15 (Model_D) to 25 km s$^{-1}$ (Model_A) at the end of the simulations. Moreover, only a small amount of $0.013$ (Model_C) to $0.016 M_{\odot}$ (Model_D) of H-rich material is removed (ablation-stripping) from the companion stars due to the SN impact (see Table 1).

For a comparison, numerical results for a classical explosion model of an $M_{\text{Ch}}$ WD for normal SNe Ia, the W7 model, are also shown in Table 1. Because the N5def model does not burn the complete WD, but rather leaves behind a $\sim 1.0 M_{\odot}$ bound remnant, it produces a much lower kinetic energy ($1.34 \times 10^{50}$ erg) than the W7 model ($1.23 \times 10^{51}$ erg). Therefore, a much smaller

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7 We expect that a somewhat lower velocity (lower kinetic energies of SN ejecta) in the direction opposite to the one-sided ignition region would lead to a slightly smaller total stripped mass.
8 Our previous work has concluded that it is sufficient to represent the companion stars with about 6 million SPH particles in the impact simulations to study the amount of unbound companion mass caused by the SN impact (see Liu et al. 2012).
amount of H-rich material of only $\sim 0.015 \, M_\odot$ is removed from the companion stars by the impact of the pure deflagration explosion of an $M_{\text{Ch}}$ WD. In contrast, the amount of the final unbound companion mass is more than 10 times larger ($> 0.1 \, M_\odot$) for the W7 explosion model with the same companion star models at the same separations.

A large amount of unbound companion mass in the impact simulations for the W7 explosion model seems to indicate that normal SNe Ia are not likely produced from the WD+MS $M_{\text{Ch}}$ explosion scenario (see also Liu et al. 2012). Here, it is shown that the mass stripping is inefficient for 2002cx-like SNe Ia due to the low kinetic energies of off-center pure deflagration explosions of an $M_{\text{Ch}}$ WD, leading to the conclusion that the amount of unbound companion material caused by the SN impact is quite small. Therefore, the H lines probably will be hidden in the late-time spectra of SN 2002cx-like SNe Ia. However, determining whether or not such a small amount of stripped H mass would show a signature of H lines in the late-time spectra of these events to obtain the lower limit of stripped mass for detecting the H lines.\(^9\)

4. POPULATION SYNTHESIS RESULTS

4.1. Power-law Fitting

Different WD+MS binary systems evolve to different evolutionary stages and have different binary parameters when the WD explodes as an SN Ia. Consequently, the companion radius and binary separation of binary systems differ significantly from the MS companion models used in our present simulations. We therefore investigated the dependence of the numerical results on the ratio of binary separation to the companion radius ($a_f/R_{2,t}$) at the time of the explosion. Here, we used the same method as in Liu et al. (2012) to artificially adjust the binary separations for a fixed companion star model (which means that all parameters but the orbital separation are kept constant).

Figure 4 presents the amount of final unbound companion mass and kick velocity as a function of the parameter of $a_f/R_{2,t}$ for four companion star models. It shows that the unbound mass and kick velocity significantly decrease when increasing the orbital separation of the binary. Generally, these relations can be fitted with power-law functions in good approximation (see Figure 4):

$$M_{\text{unbound}} = C_1 \left( \frac{a_f}{R_{2,t}} \right)^{-\alpha} \, M_\odot,$$

$$v_{\text{kick}} = C_2 \left( \frac{a_f}{R_{2,t}} \right)^{-\beta} \, \text{km s}^{-1},$$

where $a_f$ is the binary separation and $R_{2,t}$ is the radius of the MS companion star at the onset of the SN explosion. $C_1$ and $C_2$ are two constants, and $\alpha$ and $\beta$ are the power-law indices (see Table 2).

4.2. Unbound Masses and Kick Velocities

Wang et al. (2010, hereafter WLH10) performed comprehensive binary population synthesis (BPS) calculations obtaining a large sample of WD+MS SN Ia progenitor models. They predicted many properties of the companion stars and binary systems at the moment of the SN explosion (e.g., the companion masses, the companion radii, the orbital periods). The distributions of the ratio of binary separations to the companion radii ($a_f/R_{2,t}$) in the WLH10 sample (their model with $\alpha_{\text{CE}} \times \lambda = 0.5, 1.5$) are presented in Figure 5. It shows that most systems are concentrated at $a_f/R_{2,t} \sim 2.9$ and 3.4. Based on the distribution of $a_f/R_{2,t}$, we calculated the final unbound

| Model | $C_1$ | $\alpha$ | $C_2$ | $\beta$ |
|-------|-------|---------|-------|---------|
| Model_A | 1.169 | 4.345 | 258.7 | 2.354 |
| model_B | 0.251 | 3.003 | 201.9 | 2.254 |
| Model_C | 0.923 | 4.153 | 104.8 | 2.100 |
| model_D | 0.279 | 3.300 | 96.8 | 2.203 |

\(^9\) Observationally, Leonard (2007) found that the limit for detecting stripped H in nebular spectra of normal SNe Ia is 0.01 $M_\odot$ (see also Lundqvist et al. 2013).
companion masses (and kick velocities) due to the SN impact by adopting the power-law relations of four companion star models in Figure 4, which are displayed in Figure 6. As is shown, the impact of off-center pure deflagration explosions of $M_{\text{Ch}}$ WDs lead to a small amount of mass loss of the companion star ($\lesssim 0.015 M_\odot$) in almost all WD+MS binary systems from BPS calculations. Moreover, the SN impact delivers a small kick velocity of $\lesssim 25 \text{km s}^{-1}$ to the companion star.

In Section 2, initial MS companion star models were set up with an H abundance of $X = 0.7$, an He abundance of $Y = 0.28$, and a metallicity of $Z = 0.02$ when we constructed the MS companion star model at the moment of the SN explosion. Therefore, pure deflagrations of the $M_{\text{Ch}}$ WDs strip off a small amount of pure H of $\lesssim 0.01 M_\odot$ from the companion stars in almost all WD+MS models. These small stripped H masses are consistent with the lower mass limit for detecting H$\alpha$ emission lines in nebular spectra of normal SNe Ia (0.01 $M_\odot$; see Leonard 2007). The inefficient mass stripping seems to imply that the stripped H may be hidden in (observed) late-time spectra of most SN 2002cx-like SNe Ia. However, only normal SNe Ia were looked at when Leonard (2007) obtained the upper limit for the non-detection of stripped H$\alpha$ of 0.01 $M_\odot$. The observational limits for SN 2002cx-like SNe Ia may be smaller/larger than the value for normal SNe Ia. Most of the stripped H-rich material in this simulation ends up at velocities below $10^3 \text{km s}^{-1}$, so that it is confined to the innermost part of explosion ejecta. Whether or not H$\alpha$ emissions will be detectable can only be answered by performing sophisticated radiative-transfer simulations on the abundance structure of our explosion models.

5. DISCUSSION

5.1. The Influence of the Companion Structures

To test the influence of the ratio of binary separation to the companion radius $a_\ell/R_{2,\ell}$, we artificially adjusted the binary separation for a fixed companion star model. The final unbound mass due to the SN impact decreases by a factor of 10 as the parameter of $a_\ell/R_{2,\ell}$ increases by a factor of 2.

Figure 4 shows that the fitting parameters of four different companion models are different, which indicates that the companion structure results from the characteristics of the original binary system, and the details of the mass transfer can also affect the final unbound mass. In reality, the companion structure is not independent of the binary separation in the binary evolutions. Therefore, the companion structure would be different with different $a_\ell/R_{2,\ell}$ from BPS calculations.

In Section 4.2, we only used the same power-law relation obtained from a fixed companion star model (for example, the power-law relation in Model_A) to calculate the total mass loss of the companion star caused by the SN impact for all WD+MS models, which ignores the influence of details of the companion structure. Figure 6 shows a comparison of the results that were calculated by using four different power-law relations between the final unbound mass and the kick velocities and the parameter of $a_\ell/R_{2,\ell}$ in Model_A, Model_B, Model_C, and Model_D. Some differences (but not big differences) in the distribution of final unbound masses are seen in Figures 6(a) and (c), which implies that the parameter of $a_\ell/R_{2,\ell}$ is not the only factor to determine the final stripped companion mass; the companion structure can also affect the results.

5.2. Explosion Energy

For a comparison, we performed the impact simulations for the same companion star by adopting both the N5def model and the W7 explosion model to represent the SN Ia explosion. A factor of 10 lower explosion energy in the N5def model leads to the stripped material reduced by a factor of 10 (see Table 1). Moreover, Pakmor et al. (2008) investigated the influence of the SN explosion energy on the interaction with the companion star. They also found that the explosion energy range covers a factor of 2, and therefore the unbound companion mass varies by a factor of 2. These results indicate that the SN explosion energy has only a small effect on the total mass loss of the companion star as compared to the effect of the parameter of $a_\ell/R_{2,\ell}$ discussed above. Therefore, the ratio of the binary separation to the radius of the companion star ($a_\ell/R_{2,\ell}$) is the most important parameter to determine the final unbound companion mass (see also Liu et al. 2012, 2013b).

5.3. The Class of SN 2002cx-like SNe

SN 2002cx was discovered as a new class of peculiar SNe Ia by Li et al. (2003). From a volume-limited sample of the Lick Observatory Supernova Search (LOSS), Li et al. (2003) estimate that SN 2002cx-like SNe Ia contribute about 5% to the total SN Ia rate. Very recently, Foley et al. (2013) concluded that “SNe Iax” (the prototype of which is SN 2002cx) are the most common peculiar class of SNe; they estimated that in a given volume SNe Iax could contribute $\sim 1/3$ of the total SNe Ia. Nonetheless, to date, only 25 SNe Iax are confirmed to be observationally similar to their prototypical member, SN 2002cx (see Foley et al. 2013). This sample consists of 25 members and is a very small fraction of total SNe Ia. In this work, the results obtained from the impact simulations only apply to the subclass of peculiar 2002cx-like SNe but not to the bulk of SNe Ia. Therefore, even if the off-center pure deflagration explosion of an $M_{\text{Ch}}$ WD removes H-rich material during the interaction with the MS companion star, the H stripped from the companion star may not be observed in the ejecta of such relatively rare events.
Figure 6. Distributions of the final unbound companion mass (first column) and the kick velocity (second column) due to the SN impact in the simulations. Different colors show the results that are calculated by using the relation obtained from the power-law fitting (see Figure 4) for Model_A (blue lines), Model_B (red lines), Model_C (green lines), and Model_D (yellow lines). The solid (top row) and dash-dotted lines (bottom row) show results of the models with $\alpha_{\text{CE}} = 0.5$ and $\alpha_{\text{CE}} = 1.5$, respectively, in WLH10. (A color version of this figure is available in the online journal.)

5.4. Post-explosion Fate of the Binary

In this work, the N5def pure deflagration model was used to represent the SN Ia explosion in our impact simulations. The hydrodynamics calculations of Jordan et al. (2012) and Kromer et al. (2013) showed that the N5def model does not burn the complete WD, but leaves behind a $\sim 1.0\, M_\odot$ bound remnant. Unfortunately, this bound remnant cannot be spatially resolved until late-time in hydrodynamical simulations due to the strong expansion of the SN ejecta.

Our simulations show that the companion star receives a small kick velocity ($< 30\, \text{km s}^{-1}$) during the interaction with the SN ejecta. Therefore, whether or not the WD+MS binary system would be destroyed after the SN explosion depends primarily on the kick velocity of the bound remnant. If the bound remnant receives a large kick velocity that can overcome its gravitational force, abundance-enriched MS-like stars and WDs with peculiar spatial velocities are indicators (Jordan et al. 2012) of this studied progenitor scenario. Otherwise, the new binary system would survive the SN explosion.\footnote{After the SN explosion, it is found that the bound remnant receives small kick velocities of $\sim 36\, \text{km s}^{-1}$ (see Kromer et al. 2013) or large kick velocities up to $520\, \text{km s}^{-1}$ (see Jordan et al. 2012). The difference of kick velocity of the bound remnant may originate from the different gravity solvers used.}

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caused by the SN heating. This indicates that the surviving binary system may evolve and merge into a single object with a rapid rotation velocity, or experience a common envelope phase. The details of this post-explosion evolution should be addressed in future work. However, fully resolving the detailed structure of the bound remnants is a prerequisite for this investigation.

6. SUMMARY AND CONCLUSIONS

We presented 3D hydrodynamical simulations of the impact of SN Ia explosions on their companion stars for the WD+MS scenario for the pure deflagration model presented in Kromer et al. (2013). For four different companion star models, we find that the much lower kinetic energy of the pure deflagration model compared to models for normal SNe Ia leads to a much lower stripped H-rich mass of only $0.013-0.016 \, M_\odot$.

Moreover, using the distribution of $a/R_{2,0}$ from BPS calculations, we discussed the distribution of the amount of unbound H-rich material of the companion star using a power-law relation between the total unbound mass and the ratio of binary separation to the companion radius ($a/R_{2,0}$). We find that the off-center pure deflagration explosions strip off a small amount of H ($\lesssim 0.01 \, M_\odot$) from MS companion stars in most WD+MS progenitor models of SN 2002cx-like SNe Ia. The inefficient mass stripping leads to a small amount of stripped H, which may be fully hidden in late-time spectra of 2002cx-like SNe since the amount of stripped H is quite small. Therefore, it will be very interesting to analyze late-time spectra of 2002cx-like SNe Ia for the presence of hydrogen emission.

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11 However, the effect of the 1.03 $M_\odot$ bound remnant of the $M_{bd}$ WD was not considered in our impact simulations.