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HELIUM-IGNITED VIOLENT MERGERS AS A UNIFIED MODEL FOR NORMAL AND RAPIDLY DECLINING TYPE IA SUPERNOVAE

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ABSTRACT

The progenitors of Type Ia Supernovae (SNe Ia) are still unknown, despite significant progress during the last years in theory and observations. Violent mergers of two carbon–oxygen (CO) white dwarfs (WDs) are one candidate suggested to be responsible for at least a significant fraction of normal SNe Ia. Here, we simulate the merger of two CO WDs using a moving-mesh code that allows for the inclusion of thin helium (He) shells ($0.01\,M_{\odot}$) on top of the WDs, at an unprecedented numerical resolution. The accretion of He onto the primary WD leads to the formation of a detonation in its He shell. This detonation propagates around the CO WD and sends a converging shock wave into its core, known to robustly trigger a second detonation, as in the well-known double-detonation scenario for He-accreting CO WDs. However, in contrast to that scenario where a massive He shell is required to form a detonation through thermal instability, here the He detonation is ignited dynamically. Accordingly the required He-shell mass is significantly smaller, and hence its burning products are unlikely to affect the optical display of the explosion. We show that this scenario, which works for CO primary WDs with CO- as well as He-WD companions, has the potential to explain the different brightness distributions, delay times and relative rates of normal and fast declining SNe Ia. Finally, we discuss extensions to our unified merger model needed to obtain a comprehensive picture of the full observed diversity of SNe Ia.

Subject headings: Supernovae: general, white dwarfs, binaries: close

1. INTRODUCTION

Historically, Type Ia supernovae (SNe Ia) have been believed to be a uniform class of objects. However, over the past two decades large supernova surveys have revealed that this class is in fact rather inhomogeneous. Nonetheless, until recently, it has been argued that most – if not all – SNe Ia originate from delayed detonations of Chandrasekhar-mass carbon–oxygen (CO) White Dwarfs (WDs) accreting hydrogen-rich material from a non-degenerate companion star (e.g. Mazzali et al. 2007).

Lately, however, an increasing number of observational constraints have challenged this idea. In particular, the very nearby normal SN Ia 2011fe did not show any signs of a companion star (Li et al. 2011; Bloom et al. 2012), nor any signature of hydrogen in nebular spectra (Shappee et al. 2013) which is expected in the single-degenerate scenario owing to material stripped from the companion (Marietta et al. 2000; Leonard 2007). Moreover, there is a growing number of SN Ia remnants in which no remaining companion star could be found (e.g. Schaefer & Pagnotta 2012; González Hernández et al. 2012). Also, population-synthesis studies predict that the expected rate of single-degenerate Chandrasekhar-mass explosions is at least a factor of a few below the observed rate (e.g. Ruiter et al. 2009; Mennekens et al. 2010, but see Han & Podsiadlowski 2004).

Double-degenerate systems, in contrast, avoid most of these problems: there is no surviving companion star expected and they can naturally explain the absence of hydrogen features in late-time spectra. At the same time, recent first-principle three-dimensional simulations of violent mergers of two CO WDs reproduce subluminous and normal SNe Ia well (Pakmor et al. 2010, 2012b; Röpke et al. 2012). However, it is debated whether the temperature and density conditions on the surface of the WD, reached in the simulations, are sufficient to form a carbon detonation (Pakmor et al. 2010; Dan et al. 2011; Raskin et al. 2012; Pakmor et al. 2012b).

Here, we present a new three-dimensional simulation of the merger of two massive CO WDs using, for the first time in supernova modelling, the moving-mesh code AREPO (Springel 2010). AREPO allows for an highly adaptive resolution and thus the inclusion of thin helium (He) shells on top of the CO WDs. We show how this presence of He in the binary system leads to a robust explosion mechanism for violent mergers.

In Sect. 2 we present our new simulation. We then discuss the implications of the new ignition mechanism that naturally leads to two distinct populations of SNe Ia in Sect. 3. Sect. 4 presents the expected brightness distributions, rates and delay times of both populations in the context of observational constraints. We conclude with a brief summary and outlook in Sect. 5.

2. HELIUM-IGNITED VIOLENT MERGERS

We simulate the merger of a $1.1\,M_{\odot}$ CO WD and a $0.9\,M_{\odot}$ CO WD using the moving-mesh code AREPO (Springel 2010), which we extended with the same degenerate equation of state and nuclear-reaction network as described in Pakmor et al. (2012a). Specifically, in our simulation we use a 13-isotope α-network which is active for cells with temperature $> 10^6\,$K, unless $\nabla \cdot \mathbf{v} < 0$ and $|\nabla P|\, r_{\rm cell}/P > 0.33$ (following Seitenzahl et al. 2009).

We operate AREPO in the moving-mesh mode (Springel 2010), i.e. mesh-generating points move with the fluid velocity of their respective cell and a small correction to keep the grid regular. In addition, we employ explicit refinement to keep the mass of the cells within a factor of two of a given

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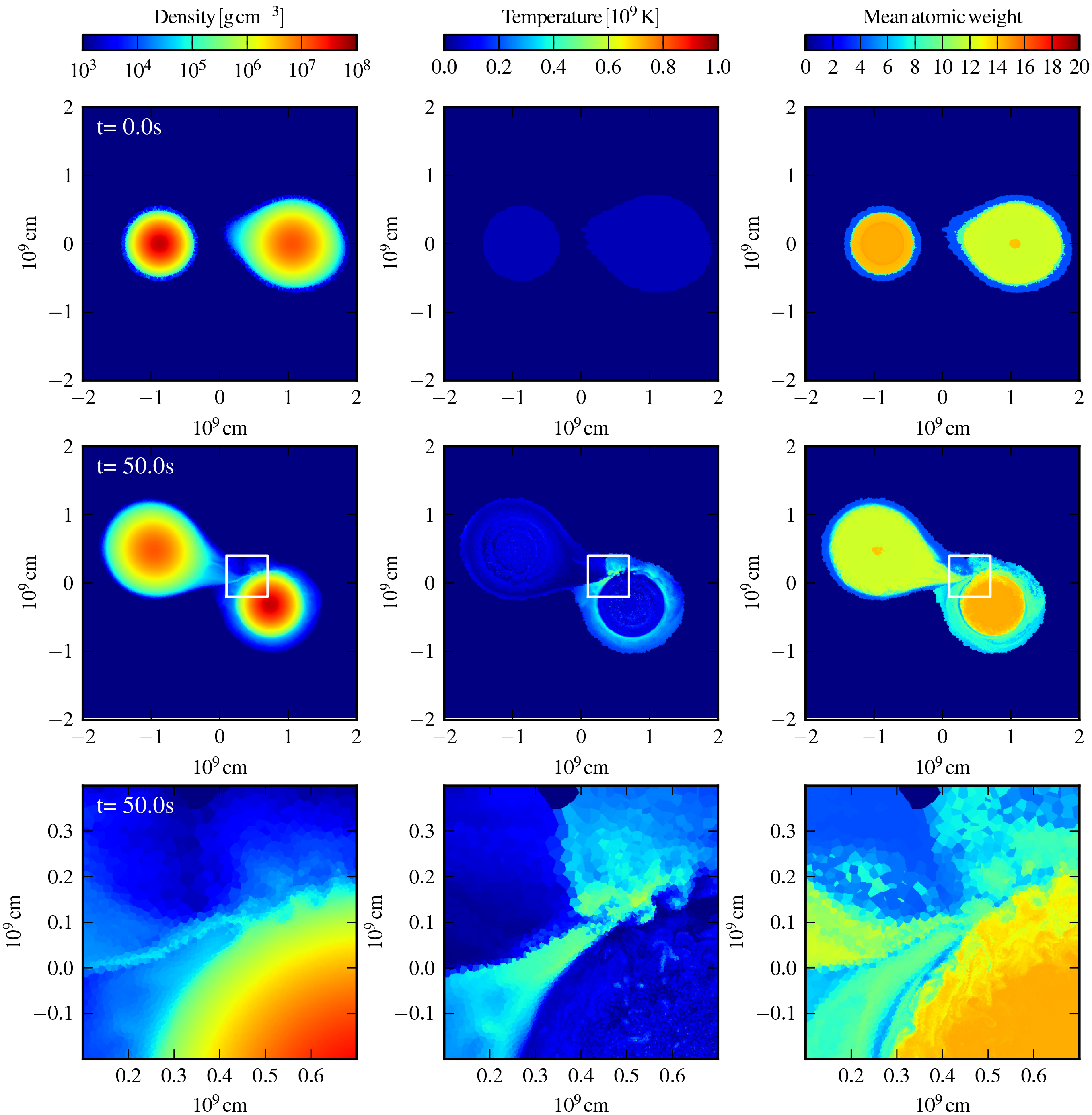

Figure 1. Time evolution of density, temperature and mean atomic weight (columns from left to right) slices in the orbital plane for our simulation of the merger of a 1.1 $M_\odot$ with a 0.9 $M_\odot$ CO WD (shown are slices in the plane of rotation). The bottom row shows enlargements of the area marked by the white boxes in the second row.

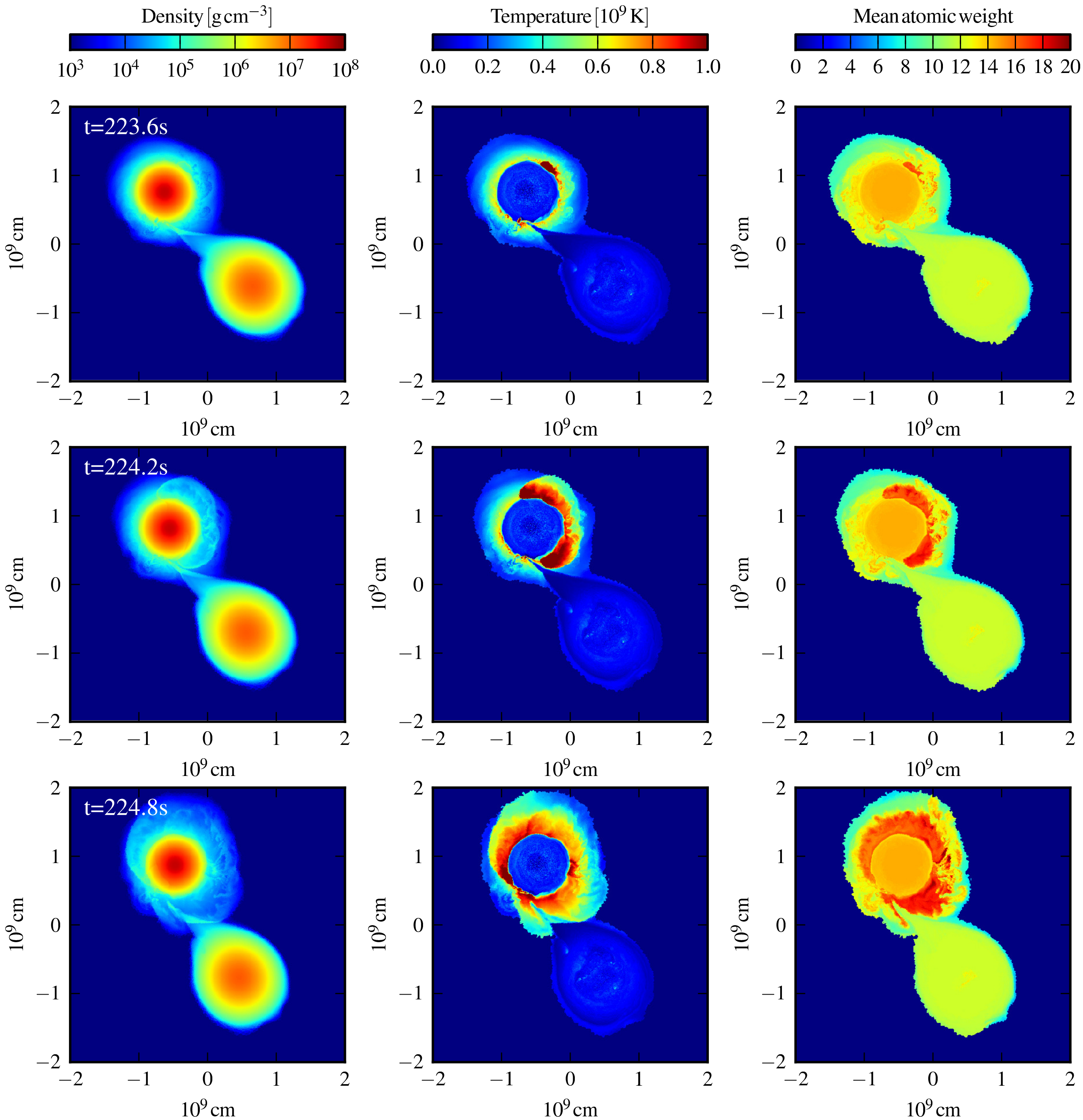

Figure 2. As Fig. 1, but showing the later stages of the merger, when the He detonation forms on the surface of the primary.

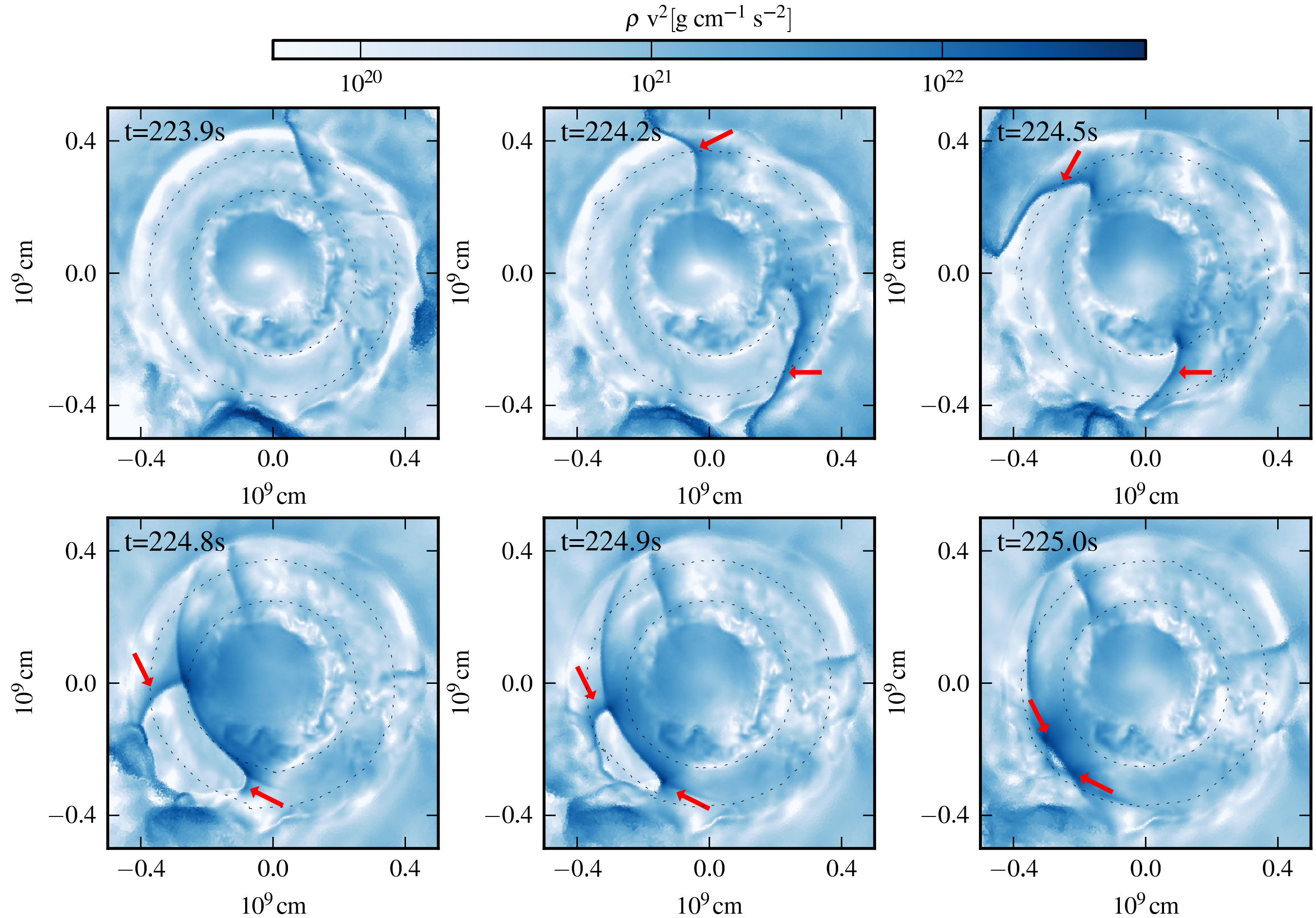

Figure 3. Slices of specific kinetic energy of the primary WD material after the orbital velocity of the binary system and an approximate solid-body spin of the primary WD have been removed (dotted black lines show density contours for $2 \times 10^6\,\mathrm{g\,cm^{-3}}$ and $10^7\,\mathrm{g\,cm^{-3}}$). A shock (marked by red arrows) emerges from the He detonation, propagates around the primary and converges in its CO core.

target mass and to guarantee a maximum volume difference between neighboring cells of a factor of 10. In this mode, AREPO is almost Lagrangian and significantly reduces advection errors compared to static grid codes. At the same time, AREPO does not suffer from artificial viscosity, sampling noise and the large errors in gradient estimates typical of SPH codes.

2.1. *Setup*

We construct binary initial conditions the same way as in Pakmor et al. (2012b), using the GADGET code (Springel 2005; Pakmor et al. 2012a). We map the binary initial conditions to AREPO by converting the SPH particles to Voronoi-cells that carry the mass and momentum of the former SPH particles. We set the temperature to $5 \times 10^7\,\mathrm{K}$ for all cells to remove temperature noise introduced in SPH. The binary is placed at the center of a $10^{12}\,\mathrm{cm}$ wide box with low background density ($10^{-5}\,\mathrm{g\,cm^{-3}}$).

In contrast to Pakmor et al. (2012b), we use composition profiles from Iben & Tutukov (1985) to construct the two WDs. To be able to resolve the He shell on the surface of both WDs, we increase the amount of He for both WDs to a total of $0.01\,M_\odot$. This is done by changing the composition in the outermost $0.005\,M_\odot$ of the WDs to pure He and the following $0.01\,M_\odot$ to a composition of 50% He, 30% C and 20% O.

We start the actual AREPO simulation with a mass resolution of $1.1 \times 10^{-7}\,M_\odot$ everywhere. During the first second, we decrease the target mass of the cells in the He shell linearly with time by a factor of 10 to a final mass resolution of $1.1 \times 10^{-8}\,M_\odot$ at $t = 1\,\mathrm{s}$. The He shell is tracked using a passive scalar.

2.2. *Simulation results*

The initial setup and evolution is shown in Fig. 1. As mass and angular momentum are transferred to the primary WD, it heats up at the surface and its outer layers start to spin relative to its core. This leads to the development of Kelvin-Helmholtz instabilities between the He shell and the CO core of the primary WD. Over time, the He is mixed with CO material and after a few orbits there is no pure He layer anymore. Moreover, He starts to burn episodically on the surface of the primary, but does not form a detonation at first.

As the orbit of the binary system shrinks, mass transfer becomes faster and more violent. After about 7 orbits, when the orbital period has decreased to about 30 s, a He detonation forms close to the surface of the CO core of the primary WD in a region compressed by a shock in the He layer. Before nuclear burning starts, this region has a temperature of $\sim 5 \times 10^8\,\mathrm{K}$, a density of $\sim 2.5 \times 10^5\,\mathrm{g\,cm^{-3}}$ and a composition of roughly equal parts of He, C and O by mass. It is resolved by cells with a radius of 30–40 km.

Note that the detonation forms dynamically, similar to previous results by Guillochon et al. (2010) for systems with high He accretion rates on CO primaries, rather than by thermal instabilities in stably-accreting steadily-burning systems (see, e.g., Shen et al. 2010). This implies that a He detonation can form for smaller He shells than in steadily-He-burning systems (Bildsten et al. 2007) as long as the accretion rate becomes high enough to ignite the He shell dynamically and there is sufficient He in the outer layers of the primary WD to form a detonation at all (see, e.g., Moll & Woosley 2013). This likely includes most CO WD primaries with outer He shells and binaries where the companion can transfer enough He to the primary before the system merges, in particular for He WD companions.

In our simulation, the He detonation propagates around the primary WD's surface (Fig. 2), sending a shock wave into its CO core, that converges in one point in the core (Fig. 3). From two- and three-dimensional simulations sub-Chandrasekhar-mass explosions (Fink et al. 2007, 2010; Moll & Woosley 2013), we know that such a converging shock inevitably leads to the formation of a subsequent C detonation. In our three-dimensional full merger simulation, however, we cannot resolve the convergence region well enough to follow the ignition of this detonation directly.

In our simulation the secondary WD is still intact at the time the detonation emerges, which makes it significantly different from previous simulations of similar systems that included a comparably massive He shell (Raskin et al. 2012). In those simulations, the He detonation only ignites when the secondary WD is already in the process of merging, and the He detonation is localized and does not propagate around the primary WD. The differences are most likely the result of different hydro schemes and the significantly higher resolution we use in the He shell (factor ~ 100 in mass). However, it is possible that the time when He detonates depends on the masses of the two WDs and that systems with low-mass primaries and smaller accretion rates only detonate during the actual merger.

3. THE OBSERVATIONAL DISPLAY OF VIOLENT MERGERS

The explosion mechanism described above directly suggests that there are at least two different populations of SNe Ia, which originate from explosions in pairs of CO WDs and CO/He WDs, respectively.

In both populations, the amount of ^{56}Ni synthesized in the explosion, and therefore the intrinsic brightness, correlates directly with the mass of the CO primary WD, since the central density of the secondary WD is always below the threshold for ^{56}Ni production at the time of detonation. However, depending on the nature of the secondary WD (He or CO), the total mass of the ejecta changes. Moreover, the interaction of the ashes of the primary with the secondary WD may lead to its destruction, either by subsequent nuclear burning in the secondary or, for low-mass WDs, by the impact of the shock-wave alone. In both cases, the density profile and composition structure of the ejecta are changed, which directly affects observables.

Carbon-ignited violent mergers of two CO WDs have already been shown to reproduce the light curves and spectra of normal SNe Ia fairly well (Pakmor et al. 2012b; Röpke et al. 2012). Whether this holds for He-ignited violent mergers has to be investigated by detailed simulations. In He-accreting sub-Chandrasekhar-mass double-detonation models the spectral properties are highly sensitive to the burning products of the He shell (e.g. Kromer et al. 2010). However, in these models it is assumed that the He shell grows massive enough to be ignited by a thermal instability (Bildsten et al. 2007). In contrast, in our merger model, for a given primary WD mass the He shell is less massive. Moreover, the He shell may be significantly mixed with CO material (see Sect. 2.2), preventing the He from synthesizing iron-group elements in the detonation (in our simulation the helium detonation synthesizes only $2 \times 10^{-8}\,M_\odot$ of elements heavier than Calcium). Therefore, it is conceivable that in our scenario the ashes of the He shell will have little or no effect on spectra and light curves.

It has also been shown that mergers of two low-mass CO WDs reproduce colors and spectra of objects similar to SN 1991bg very well (Pakmor et al. 2010). However, such mergers fail to reproduce the narrow, fast evolving light curves of 1991bg-like SNe. The light curve width of SNe Ia is mainly set by the amount of ^{56}Ni synthesized during the explosion since the ^{56}Ni provides a significant part of the total opacity of the ejecta. As a consequence brighter explosions have typically more slowly declining light curves. For a given ^{56}Ni mass, however, the total ejecta mass will also affect the light-curve width. We therefore propose that the progenitors of fast declining SNe Ia (most notably 1991bg-like objects) might be binaries of He and CO WDs. The narrow light curves could then be understood as a natural consequence of the smaller ejecta mass. At the same time, the spectral properties and colors of the explosion could be expected not to change drastically compared to a merger of two CO WDs with the same primary mass, since the secondary WD, which is burned after the primary, only affects the central parts of the ejecta (Pakmor et al. 2012b).

4. BRIGHTNESS DISTRIBUTIONS, RATES AND DELAY TIMES

To explain the observed diversity of SNe Ia with a theoretical model, it is necessary to reproduce not only light curves and spectra of single objects, but also the brightness distribution of objects of different sub-classes, their relative rates, and their delay times.

In this regard, we base the analysis of our scenario on one specific population-synthesis model that has been described in a set of papers (Ruiter et al. 2009, 2011, 2013), since it is possibly the most detailed model published at the moment. Note that other population-synthesis models find somewhat different results, which introduces significant uncertainties and may alter some of our conclusions.

Ruiter et al. (2013) have shown that carbon-ignited violent mergers of two CO WDs can not only explain the brightness distribution of normal SNe Ia but also their observed delay-time distribution and rates. Moreover, they found a tendency that mergers with more massive primary WDs, which lead to brighter supernovae, preferentially occur in younger populations, consistent with observed trends (see e.g. Gupta et al. 2011). However, Ruiter et al. (2013) find not enough systems to account for the observed number of faint SNe. In nature those have predominantly fast light curves similar to SN 1991bg (see Fig. 4), but there seems to emerge a sparse population with low luminosities yet slowly evolving light curves similar to SN 2002es and PTF10ops (Maguire et al. 2011; Ganeshalingam et al. 2012, see also Fig. 4) which might be consistent with the mergers of low-mass CO WD binaries.

In contrast to mergers of two CO WDs, the distribution of mass-transferring CO/He WD binaries has a strong peak between $0.8\,M_\odot$ and $0.9\,M_\odot$ for the mass of the primary WD

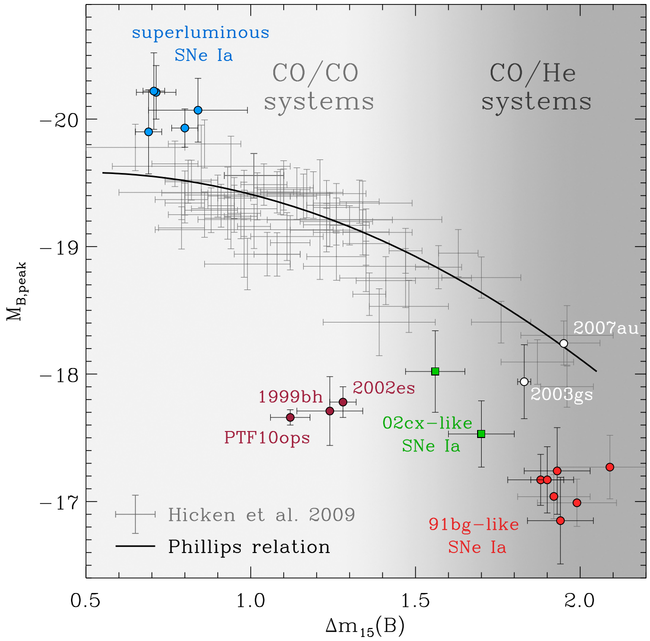

Figure 4. Observed diversity of SNe Ia in $\Delta m_{15}(B)$ vs. $M_{B,\mathrm{peak}}$ space as found in a sub-sample of the data presented in tables 8 and 9 of Hicken et al. (2009) where SNe without a $\Delta m_{15}(B)$ measurement and a distance modulus $\mu \leq 33$ mag have been removed. Most of these SNe Ia are normal and follow the Phillips et al. (1999) relation. Additional datapoints (Phillips et al. 2007; Taubenberger et al. 2008, 2011; Krisciunas et al. 2009; Maguire et al. 2011; Ganeshalingam et al. 2012) have been included to indicate the position of the peculiar sub-classes discussed in the text. Except for 2002cx-like SNe, our unified merger model potentially explains the full observed diversity. Explosions in CO/CO binaries are expected to have more slowly declining light curves than those in CO/He binaries (indicated by the background-color gradient).

(Ruiter et al. 2011). Although stable mass transfer is assumed for the binary systems discussed in Ruiter et al. (2011), we argue that a significant fraction of them may cause a dynamical He detonation on the surface of the primary WD (Guillochon et al. 2010), long before a sufficient amount of He has been accumulated on the primary WD to ignite due to thermal instabilities. Since a dynamical detonation occurs, in this case, soon after mass transfer sets in, the core mass of a CO WD in Ruiter et al. (2011) is still a good indicator for the absolute brightness of the subsequent explosion. In general, binaries with a He WD secondary should therefore lead to fainter explosions since their primaries are typically significantly less massive than those of CO WD binaries.

Mergers with a primary WD mass around $0.9\,M_\odot$ should produce a ^{56}Ni mass close to that required for 1991bg-like SNe Ia (Pakmor et al. 2010; Sim et al. 2010). For those primary masses, the rate of potentially exploding CO/He WD binaries dominates over that of pure CO WD binaries (Ruiter et al. 2011). Since these systems will have narrow light curves (see discussion above) they would naturally explain the population of 1991bg-like SNe. Moreover, the very long delay times of these explosions (> 1 Gyr; Ruiter et al. 2011) are in good agreement with the observed tendency of 1991bg-like SNe to arise in old stellar populations.

Population synthesis calculations also find a sparsely populated tail of CO/He WD binaries towards larger primary masses (Ruiter et al. 2011). Explosions of such systems can reach luminosities more typical for normal SNe Ia but should still have faster light curves similar to 1991bg-like SNe. Observationally, these events might be identified with objects

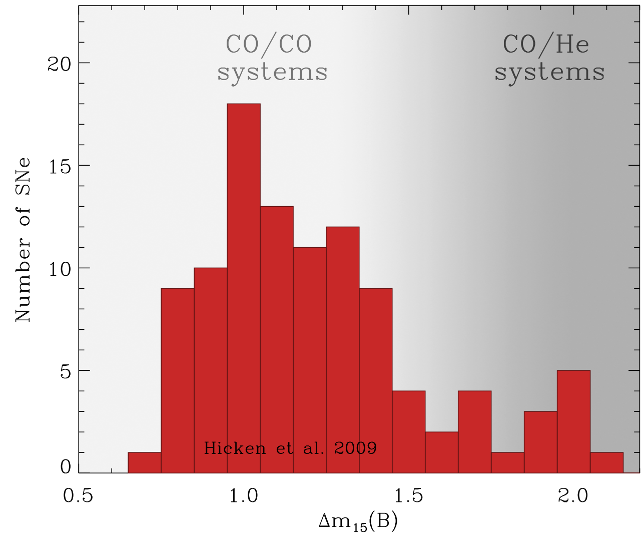

Figure 5. Histogram of the observed number of SNe Ia as a function of $\Delta m_{15}(B)$ (data from table 9 of Hicken et al. (2009)). The distribution shows some indication for bimodality which might be identified with the two different companion populations in our model (illustrated by the background-color gradient as in Fig. 4).

like SN 2003gs or SN 2007au (Krisciunas et al. 2009; Hicken et al. 2009, see Fig. 4).

It is interesting to note that the two populations might also provide a natural explanation for the observed bimodal distribution of SNe Ia in $\Delta m_{15}(B)$-space which some SN data sets suggest (see Fig. 5). The population synthesis calculations of Ruiter et al. (2009) predict a total SN Ia rate that is comparable to the Galactic SN Ia rate if both double-degenerate mergers with a total mass above the Chandrasekhar-limit and single-degenerate Chandrasekhar-mass models are considered. Hydrogen-accreting single-degenerate systems, however, contribute only ~ 3 per cent to this total rate. Therefore it seems unlikely that the bimodal distribution in $\Delta m_{15}(B)$-space can be attributed to contributions from single-degenerate and double-degenerate progenitor systems.

5. SUMMARY AND DISCUSSION

In this paper, we have presented a new simulation of the merger of two CO WDs including thin He shells. We have shown that the presence of only $0.01\,M_\odot$ of He is sufficient to ignite a detonation in the He shell of the primary WD. This leads to a robust ignition mechanism for CO WD binaries that are about to merge. As in the double-detonation explosion scenario for He-accreting sub-Chandrasekhar-mass WDs, this He detonation subsequently sends a converging shock into the underlying CO core which leads to a detonation in the core and completely unbinds the progenitor stars.

The new scenario works independently of the nature of the secondary (He or CO) WD. We have argued that the two types of progenitor systems lead to two distinct populations of SNe Ia: mostly faint, fast declining objects for He companions and bright, slowly declining SNe for CO companions. This may naturally explain the observed bi-modality of SNe Ia in $\Delta m_{15}(B)$ space. We have also shown that population synthesis qualitatively predicts brightness distributions, relative rates and delay times for these two populations in agreement with observational data of normal and subluminous SNe Ia.

Other observational sub-classes can be easily incorporated into our scenario. SNe Ia with signs of CSM interaction (see, e.g., Patat et al. 2007; Dilday et al. 2012) can be interpreted as double-degenerate systems exploding shortly after the last common-envelope phase (Livio & Riess 2003; Soker et al. 2013). Superluminous SNe Ia, which are significantly brighter than normal SNe Ia, have recently been argued to originate from a merger of two massive WDs without a prompt detonation (Hachinger et al. 2012; Taubenberger et al. 2013). In our scenario these might be explained by very He-poor binary systems with two massive CO WDs.

The only objects that can probably not be accounted for by pure detonations are 2002cx-like SNe (Jha et al. 2006). But they have recently been identified with off-center-ignited pure deflagrations of Chandrasekhar-mass CO WDs (Kromer et al. 2013).

Together, our scenario may provide a first step to construct a comprehensive picture of SNe Ia that is in principle able to explain all major sub-classes including superluminous SNe Ia and SNe Ia with CSM interaction.

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REFERENCES

Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJ, 662, L95
Bloom, J. S., Kasen, D., Shen, K. J., et al. 2012, ApJ, 744, L17
Dan, M., Rosswog, S., Guillochon, J., & Ramirez-Ruiz, E. 2011, ApJ, 737, 89
Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, Science, 337, 942
Fink, M., Hillebrandt, W., & Röpke, F. K. 2007, A&A, 476, 1133
Fink, M., Röpke, F. K., Hillebrandt, W., et al. 2010, A&A, 514, A53
Ganeshalingam, M., Li, W., Filippenko, A. V., et al. 2012, ApJ, 751, 142
González Hernández, J. I., Ruiz-Lapuente, P., Tabernero, H. M., et al. 2012, Nature, 489, 533
Guillochon, J., Dan, M., Ramirez-Ruiz, E., & Rosswog, S. 2010, ApJ, 709, L64
Gupta, R. R., D'Andrea, C. B., Sako, M., et al. 2011, ApJ, 740, 92
Hachinger, S., Mazzali, P. A., Taubenberger, S., et al. 2012, MNRAS, 427, 2057
Han, Z., & Podsiadlowski, P. 2004, MNRAS, 350, 1301
Hicken, M., Challis, P., Jha, S., et al. 2009, ApJ, 700, 331
Iben, Jr., I., & Tutukov, A. V. 1985, ApJS, 58, 661
Jha, S., Kirshner, R. P., Challis, P., et al. 2006, AJ, 131, 527
Krisciunas, K., Marion, G. H., Suntzeff, N. B., et al. 2009, AJ, 138, 1584
Kromer, M., Sim, S. A., Fink, M., et al. 2010, ApJ, 719, 1067
Kromer, M., Fink, M., Stanishev, V., et al. 2013, MNRAS, 429, 2287
Leonard, D. C. 2007, ApJ, 670, 1275
Li, W., Bloom, J. S., Podsiadlowski, P., et al. 2011, Nature, 480, 348
Livio, M., & Riess, A. G. 2003, ApJ, 594, L93
Maguire, K., Sullivan, M., Thomas, R. C., et al. 2011, MNRAS, 418, 747
Marietta, E., Burrows, A., & Fryxell, B. 2000, ApJS, 128, 615
Mazzali, P. A., Röpke, F. K., Benetti, S., & Hillebrandt, W. 2007, Science, 315, 825
Mennekens, N., Vanbeveren, D., De Greve, J. P., & De Donder, E. 2010, A&A, 515, A89
Moll, R., & Woosley, S. E. 2013, ArXiv e-prints arXiv:1303.0324
Pakmor, R., Edelmann, P., Röpke, F. K., & Hillebrandt, W. 2012a, MNRAS, 424, 2222
Pakmor, R., Kromer, M., Röpke, F. K., et al. 2010, Nature, 463, 61
Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012b, ApJ, 747, L10
Patat, F., Chandra, P., Chevalier, R., et al. 2007, Science, 317, 924
Phillips, M. M., Lira, P., Suntzeff, N. B., et al. 1999, AJ, 118, 1766
Phillips, M. M., Li, W., Frieman, J. A., et al. 2007, PASP, 119, 360
Raskin, C., Scannapieco, E., Fryer, C., Rockefeller, G., & Timmes, F. X. 2012, ApJ, 746, 62
Röpke, F. K., Kromer, M., Seitenzahl, I. R., et al. 2012, ApJ, 750, L19
Ruiter, A. J., Belczynski, K., & Fryer, C. 2009, ApJ, 699, 2026
Ruiter, A. J., Belczynski, K., Sim, S. A., et al. 2011, MNRAS, 417, 408
Ruiter, A. J., Sim, S. A., Pakmor, R., et al. 2013, MNRAS, 429, 1425
Schaefer, B. E., & Pagnotta, A. 2012, Nature, 481, 164
Seitenzahl, I. R., Meakin, C. A., Townsley, D. M., Lamb, D. Q., & Truran, J. W. 2009, ApJ, 696, 515
Shappee, B. J., Stanek, K. Z., Pogge, R. W., & Garnavich, P. M. 2013, ApJ, 762, L5
Shen, K. J., Kasen, D., Weinberg, N. N., Bildsten, L., & Scannapieco, E. 2010, ApJ, 715, 767
Sim, S. A., Röpke, F. K., Hillebrandt, W., et al. 2010, ApJ, 714, L52
Soker, N., Kashi, A., García-Berro, E., Torres, S., & Camacho, J. 2013, MNRAS, 431, 1541
Springel, V. 2005, MNRAS, 364, 1105
—. 2010, MNRAS, 401, 791
Taubenberger, S., Hachinger, S., Pignata, G., et al. 2008, MNRAS, 385, 75
Taubenberger, S., Benetti, S., Childress, M., et al. 2011, MNRAS, 412, 2735
Taubenberger, S., Kromer, M., Hachinger, S., et al. 2013, ArXiv e-prints arXiv:1304.4952