EVALUATION OF POST-IMPACT REMNANT HELIUM STARS IN TYPE Ia SUPERNOVA REMNANTS WITHIN THE SINGLE-DEGENERATE SCENARIO

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ABSTRACT

The progenitor systems of Type Ia supernovae (SNe Ia) are still under debate. Based on recent hydrodynamics simulations, non-degenerate companions in the single-degenerate scenario (SDS) should survive the supernova (SN) impact. One way to distinguish between the SDS and double-degenerate scenario is to search for post-impact remnant stars (PIRSs) in SN Ia remnants. Using a technique that combines multi-dimensional hydrodynamics simulations with one-dimensional stellar evolution simulations, we have examined the post-impact evolution of helium-rich binary companions in the SDS. It is found that these helium-rich PIRs (He PIRs) dramatically expand and evolve to a luminous phase (L \sim 10^4 L_\odot) about 10 yr after an SN explosion. Subsequently, they contract and evolve to become hot blue-subdwarf-like (sdO-like) stars by releasing gravitational energy, persisting as sdO-like stars for several million years before evolving to the helium red-giant phase. We therefore predict that a luminous OB-like star should be detectable within \sim 30 yr after the SN explosion. Thereafter, it will shrink and become an sdO-like star in the central regions of SN Ia remnants within star-forming regions for SN Ia progenitors evolved via the helium-star channel in the SDS. These He PIRs are predicted to be rapidly rotating (v_{rot} \gtrsim 50 km s^{-1}) and to have high spatial velocities (v_{linear} \gtrsim 500 km s^{-1}). Furthermore, if SN remnants have diffused away and are not recognizable at a later stage, He PIRs could be an additional source of single sdO stars and/or hypervelocity stars.

Key words: binaries: close – methods: numerical – stars: evolution – subdwarfs – supernovae: general

Online-only material: color figures

1. INTRODUCTION

The catastrophic explosions of Type Ia supernovae (SNe Ia) are of great importance in probing the history of the universe. It is generally believed that SNe Ia are caused by thermonuclear explosions of carbon–oxygen (CO) white dwarfs (WDs) in close binary systems, but their intrinsic variety and nature of their progenitor systems are still under debate (Livio 2000; Hillebrandt & Niemeyer 2000; Ruiz-Lapuente 2012; Wang & Han 2012).

Current mainstream progenitor scenarios include the single-degenerate scenario (SDS; Whelan & Iben 1973; Nomoto 1982) and the double-degenerate scenario (DDS; Iben & Tutukov 1984; Webbink 1984). In the SDS, the binary companion is a non-degenerate companion which could include stars of many different stellar types, including main-sequence (MS) stars, red giants (RGs), helium (He) stars, and M-dwarfs (Hachisu et al. 1999; Ivanova & Taam 2004; Hachisu et al. 2008; Wang et al. 2009, 2010; Wang & Han 2010a; Wheeler 2012). However, these non-degenerate companions are usually hydrogen-rich. The observational upper limit of stripped hydrogen after supernova (SN) impact is \sim 0.01 M_\odot for SN 2005am and SN 2005cf (Leonard 2007), and \sim 0.001 M_\odot for SN 2011fe (Shappee et al. 2013b). Thus, the absence of the hydrogen that should appear in SN Ia spectra poses a problem for the SDS. The DDS instead results from mergers of two CO WDs with total mass greater than the Chandrasekhar mass, avoiding the hydrogen problem. These violent events may lead to accretion-induced collapse to neutron stars instead of thermonuclear explosions (Nomoto & Iben 1985). However, estimates of the delay time distribution (DTD) based on observed SN rates are consistent with a large fraction of events being due to double-degenerate progenitors (Maoz et al. 2011, 2012).

Based on recent hydrodynamics simulations of SN Ia impact on binary companions in the SDS, including grid-based (Marietta et al. 2000; Pan et al. 2010, 2012b) and smooth particle (Pakmor et al. 2008; Liu et al. 2012) simulations, these non-degenerate companions should survive the SN impact and could be detectable. Thus, one of the simplest ways to distinguish between the SDS and DDS is to search for post-impact remnant stars (PIRSs) in Type Ia supernova remnants (Ia SNRs).

Recent PIRs searches have studied two Galactic Ia SNRs (SN 1572, Ruiz-Lapuente et al. 2004; Ibara et al. 2007; Kerzendorf et al. 2009, 2012b; González Hernández et al. 2009; and SN 1006, González Hernández et al. 2012; Kerzendorf et al. 2012a) and two Ia SNRs in the Large Magellanic Cloud (Edwards et al. 2012; Schaefer & Pagnotta 2012). So far, only M-dwarf stars and the subgiant Tycho G star have emerged as possible PIRs candidates, and they are not well matched with companion models in the standard SDS channels, a result that may favor the DDS. However, the properties of a PIRs could change significantly after the SN impact. For instance, Marietta et al. (2000) and Pan et al. (2012b) have shown that almost all the envelope of the RG in the RG-WD channel should be removed during the SN impact, and \sim 10%-20% of the MS star mass should be stripped and ablated in the MS-WD channel (Marietta et al. 2000; Pan et al. 2012b; Liu et al. 2012). Therefore, the PIRs in the RG-WD channel could be a helium pre-WD or low-mass helium-burning star with little hydrogen-rich envelope. We note that the SN impact will not only strip and ablate the mass of a non-degenerate companion star, but also compress and deposit energy into it (Pan et al. 2012b).

The evolution of PIRs has been studied by Podsiadlowski (2003) for a 1 M_\odot subgiant companion and by Shappee et al. (2013a) for a 1 M_\odot MS companion. They found that PIRs could...
be overluminous due to the energy release from the SN energy deposition, suggesting that the SDS should be ruled out for several Ia SNRs. However, in their calculations, these authors assumed ad hoc prescriptions for energy input and mass stripping without performing detailed hydrodynamical calculations and, therefore, did not accurately calculate the shock compression in the stellar interior and the depth of the energy deposition. In Pan et al. (2012a), we studied the evolution of PIRSs using a detailed treatment of SN impact via three-dimensional hydrodynamics simulations. These simulations included the symmetry-breaking effects of orbital motion, rotation of the non-degenerate companions, and Roche-lobe overflow (RLOF) for the MS-WD channel. These three-dimensional simulation results were mapped into a one-dimensional stellar evolution code to simulate the post-impact evolution. It was found that MS-like PIRSs evolve to become subgiants \( (L \sim 10-100 L_\odot) \) after a few hundred years and could be slowly rotating after stellar expansion. Although the model closest to the Tycho G star in these calculations was twice as bright, these results provide some support for Tycho G as a possible PIRS in the SDS.

A new subclass of sub-luminous SNe Ia, namely, Type Iax supernovae (SNe Iax), recently has been proposed by Foley et al. (2012). This population could originate from the He-WD channel in the SDS via a helium double-detonation explosion or by merger of an He WD with a CO WD (Foley et al. 2012; Wang et al. 2013). The He-WD channel naturally explains the absence of hydrogen lines, and two SNe Iax have shown helium lines in their spectra, suggesting that helium must be present in the progenitor systems. Pan et al. (2010, 2012b) have shown that only about \( \lesssim 5\% \) of the mass of the helium star is lost into the SNR in the He-WD channel, an amount that is much lower than the hydrogen mass lost in the MS-WD channel and the RG-WD channel. The He-WD channel mainly contributes to the prompt part of the DTD in population synthesis studies \( (\sim 45-220 \text{Myr}; \text{Wang} \& \text{Han 2010b}) \), and this is consistent with the distribution of SNe Iax, since no SNe Iax have been observed in elliptical galaxies. Finally, several He-WD binary systems with the properties required to be SN Ia progenitors have been observed, for example, KPD 1930+2752 (Maxted et al. 2000; Dubey et al. 2008), to simulate the impact of SN Ia ejecta on the binary companions, and the stellar evolution code, MESA\(^5\) (Modules for Experiments in Stellar Astrophysics; Paxton et al. 2011, 2013), to create the progenitor models and simulate the post-impact evolution. We perform the SN Ia explosion simulations and post-impact stellar evolution calculations using a technique similar to the one described in Paper II, but we focus on the He-WD channel. To link FLASH’s output with MESA’s initial stellar models, we solve the hydrostatic equilibrium equation using a fourth-order Runge–Kutta solver with adaptive stepsize control, as described in Paper III. However, the assumption of ideal gas plus radiation equation of state (EOS) is no longer valid for He star companions, where the central density and temperature are much higher than in MS-like stars. We therefore update the EOS solver to include the OPAL, SCVH, and HELM EOS tables from the eos and kap modules in MESA.

3. He STAR PROGENITOR SYSTEMS

The progenitor models are taken from the HeWDa, HeWDb, HeWDc, and HeWDd helium-star models in Paper I, but without the simplification of uniform composition. These four models were generated with initial masses equal to 1.25, 1.35, 1.4, and 1.8 \( M_\odot \) and initial metallicity \( Z = 0.02 \). An artificial constant mass-loss rate was adopted such that the evolution times and final helium-star masses were consistent with the detailed binary evolution models of Wang et al. (2009). Once the mass-loss phase ended, the stellar models were taken as initial models for the three-dimensional FLASH simulations. The physical properties of these four initial models are summarized in Table 1. All four helium-star models were relaxed on the three-dimensional grid by artificially damping the gas velocity for five dynamical timescales, ensuring that our models started in hydrostatic equilibrium and reducing the geometrical distortion introduced by passing from one dimension to three dimensions. The entropy, composition, density, and temperature of these four helium stars at the onset of the SN Ia explosion are shown in Figure 1.

Using the numerical setup and initial conditions for SN Ia explosions described in Paper II, we performed three-dimensional FLASH simulations of SN Ia explosions in close binary systems with resolutions of 6/8 adaptive mesh refinement levels (equivalent to a 1024\(^3\) uniform grid and a zone

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\(^4\) http://flash.uchicago.edu

\(^5\) http://mesa.sourceforge.net
size of 0.029 R∗; see Paper II for definition). In Paper II, we performed a convergence study and concluded that this resolution would be sufficient to adequately describe the properties of post-impact companions. The initial binary systems were assumed to be in RLOF, and the SN model used was the W7 model (Nomoto et al. 1984). Although SNe Iax are mostly sub-Chandrasekhar mass explosions, we chose the standard W7 explosion as the first case for comparison with our previous studies in Papers I and II. Since the mass loss from the non-degenerate star is sensitive to the detailed numerical setup of the SN model, we adopted the “W7 SN” sub-grid model, which has a power-law density distribution and a constant temperature distribution in radius that matches the exploding mass and energy in the W7 model (see Paper II for detailed descriptions).

After the SN Ia impact, the helium-star binary companion loses \(~4\%–6\%\) of its mass and is heated, the degree to which depends on the progenitor model (see Table 2). In addition, because of the shock interaction during the SN Ia impact, the central density of the helium star decreases to \(~20\%–30\%\) of its original value, and the central temperature decreases by \(~10\%–15\%\), except for model HeWDa. Before the SN impact, the HeWDa model has a lower central helium composition than the other three models due to central helium burning, causing a higher positive entropy gradient at about \(m/M_\odot \sim 0.5\). Therefore, in this model the central density decreases 22\% during the SN impact, while the central temperature increases by 12\%.

Figure 2 shows the bound gas density distribution for model HeWDc in the orbital plane at the end of the simulation \((t = 3106\) s). Since the companion star has a high linear speed and will eventually reach the edge of the simulation box, we cannot simulate the evolution for a sufficiently long time for the companion to be fully in hydrostatic equilibrium. However, we can assume the specific entropy and composition profiles are conserved if the system is adiabatic. To calculate the specific entropy and composition profiles, a large spherical region is considered (the black circle in Figure 2) and then divided into 128–256 radial bins. Figure 3 shows the comparison of angle-averaged bound density radial profile with the scattered threedimensional data points, and relaxed hydrostatic profiles for the model HeWDc. It is clear that the angle-averaged density profile is consistent with our reconstructed hydrostatic model which is described in the next paragraph. Figure 4 shows the angle-averaged one-dimensional radial post-impact profiles of the specific entropy, helium composition, density, and temperature at the end of the FLASH simulations.

With the eos (equation of state) and kap (opacity) module in MESA, we used the post-impact specific entropy profiles and composition profiles to construct hydrostatic models by solving the continuity and hydrostatic equations for the density \(\rho\), pressure \(P\), and radius \(r\) as functions of the enclosed mass \(m\):

\[
\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho} \tag{1}
\]

\[
\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}. \tag{2}
\]

The entropy of each mass element was kept fixed, except that the entropy profiles were flattened in the outermost region \((0.995 < m/M_\odot < 1)\) to avoid negative entropy gradients. For the HeWDa model, the composition profile was adjusted to a uniform distribution due to the strong mixing during the SN impact and to avoid negative entropy and composition gradients. The hydrostatic solutions were taken as initial conditions for the models used in MESA. It should be noted that the SN ejecta and unbound companion mass are optically thick at the end of the FLASH simulations, and therefore, the photosphere is larger.
Figure 2. Bound gas density distribution in the orbital plane for a three-dimensional SN Ia simulation with the model HeWDc in Table 1 at time 3106 s after the explosion. The black circle shows the maximum distance ($r_{\text{max}} = 8.83 \times 10^{10}$ cm) which is used for the one-dimensional model reconstruction. (A color version of this figure is available in the online journal.)

Figure 5 shows the specific entropy, helium composition, density, and temperature profiles of the relaxed helium-star models in MESA. The relaxed hydrostatic helium-star models differ somewhat in the photospheric luminosity and effective temperature, but the stellar radius and interior density and temperature profiles are nearly the same as in the original models. Figure 6 shows the changes of mass and radius before and after SN impact. Although He PIRSs only lose a few percent of their masses, post-impact radii increase by a factor of $\sim 4$ (see Table 2). These changes in radius dramatically alter the He PIRSs.

4. POST-IMPACT EVOLUTION

Once we have the relaxed hydrostatic stellar models, the post-impact evolution of He PIRSs can be easily calculated in MESA.

Table 2

| Model  | $M_{\text{SN}}$ ($M_\odot$) | $\Delta M / M_\odot$ | $R_{\text{SN}}$ ($10^{10}$ cm) | $T_{\text{eff,SN}}$ (K) | $v_{\text{linear,SN}}$ (km s$^{-1}$) | $M_{\text{Ni}}$ ($10^{-4} M_\odot$) | $E_{\text{in}}$ ($10^{59}$ erg) |
|--------|-----------------|-----------------|----------------------------|-----------------|-----------------|-----------------|-----------------|
| HeWDa  | 0.656           | 5.88            | 2.71                       | 4.30            | 0.265           | 4.03            | 734             | 15.0            | 1.3             |
| HeWDb  | 0.748           | 6.85            | 3.93                       | 3.58            | 0.510           | 4.01            | 550             | 2.38            | 1.3             |
| HeWDc  | 0.962           | 4.47            | 5.63                       | 4.17            | 0.792           | 4.01            | 509             | 5.64            | 1.5             |
| HeWDb  | 1.126           | 6.63            | 7.24                       | 4.50            | 1.16            | 4.03            | 446             | 1.75            | 1.7             |

Note: The mass ($M_{\text{SN}}$), mass change ($\Delta M = M_{\text{SN}} - M_0$), radius ($R_{\text{SN}}$), luminosity ($L_{\text{SN}}$), effective temperature ($T_{\text{eff,SN}}$), linear spatial velocity ($v_{\text{linear,SN}}$), mass of bound nickel ($M_{\text{Ni}}$), and energy deposition from the SN ejecta ($E_{\text{in}}$) of initial relaxed post-impact hydrostatic models in MESA.

than the bound companion region. However, the outflowing ejecta will become transparent in the optical wave band and the surviving star should be detectable after several months. This early influence of the dynamically moving photosphere associated with the unbound material is not considered here.

The initial luminosity profile for MESA was estimated using the radiative temperature gradient expression,

$$L(m) = -\frac{(4\pi r^2 ac) dT^4}{3\kappa} dm,$$

(3)

where $\kappa$ is the opacity, $a$ is the radiation constant, and $c$ is the speed of light. Since our initial luminosity profile is based on an assumption of radiative equilibrium and our surface profiles are not as sharp as the standard surface profile in MESA, the calculated photospheric luminosity and effective temperature were very rough at the beginning and needed to be relaxed in MESA. A fixed time step, $\Delta t = 10^{-8}$ yr, was enforced for the first $10^{-6}$ yr to relax the models. After $10^{-6}$ yr, we allowed the time step to be automatically determined in MESA.

Figure 5 shows the specific entropy, helium composition, density, and temperature profiles of the relaxed helium-star models in MESA. The relaxed hydrostatic helium-star models differ somewhat in the photospheric luminosity and effective temperature, but the stellar radius and interior density and temperature profiles are nearly the same as in the original models. Figure 6 shows the changes of mass and radius before and after SN impact. Although He PIRSs only lose a few percent of their masses, post-impact radii increase by a factor of $\sim 4$ (see Table 2). These changes in radius dramatically alter the He PIRSs.

4. POST-IMPACT EVOLUTION

Once we have the relaxed hydrostatic stellar models, the post-impact evolution of He PIRSs can be easily calculated in MESA.
In this section, we describe this evolution. Hertzsprung–Russell (H-R) diagrams of post-impact evolutionary tracks of He PIRSs are presented in luminosity versus effective temperature, surface gravity versus effective temperature, and color–magnitude forms, providing diagnostics for searches in future observations for He PIRSs in Ia SNRs.

4.1. Evolutionary Tracks

Similarly to the MS-like PIRSs in Paper III, the He PIRSs expand rapidly and dramatically due to the release of energy deposited by the SN impact. The amount of energy deposition can be calculated by tracing the amount of binding energy increased after the SN impact. Since ~5% of the mass is lost after the SN impact, the initial binding energy should exclude the energy from the regions that will eventually become unbound. We mark tracer particles that remain bound at the end of FLASH calculations and calculate the original locations of these particles at the beginning of our calculations. It is found that the energy deposition is $(1.3–1.7) \times 10^{49}$ erg in the He-WD channel (see Table 2). At RLOF, the total incident energy from SN ejecta is $3 \times 10^{49}$ erg, suggesting that 40%–60% of the energy is absorbed by the remnant helium stars. The remaining incident energy takes the form of the kinetic and thermal energy of the unbound mass of the companion, and the kinetic energy due to SN kick. Furthermore, the reverse shock during the SN impact also carries away some of the energy (see Paper II).

Figure 7 shows the evolution of the photospheric radius, luminosity, and effective temperature as functions of time. All He PIRSs expand on a timescale of ~10–30 yr, depending on their progenitor models. These expansion rates are determined by the local radiative diffusion timescale (Henyey & L’Ecuyer 1969), which is associated with not only the stellar structure, but also the amount and depth of SN energy deposition.

Since He stars are more compact than MS-like stars, the depths of energy deposition are shallower, causing a shorter local radiative diffusion timescale. Therefore, heat transfer initially occurs more rapidly than the thermal expansion. The effective temperature starts to increase at $\sim 10^{-2–10^{-1}}$ yr and then continues increasing for another $10^0–10^1$ yr up to $\sim 30,000–50,000$ K. Subsequently, the surfaces of the He PIRSs cool off to $\sim 10,000–30,000$ K on a timescale of ~10 yr due to the expansion. The stars quickly become luminous helium OB stars ($L \sim 10^3–10^4 L_\odot$). When the deposited energy has radiated away, the photospheric radii reach maximum values at around ~10–30 yr. Subsequently, the stars contract and release gravitational energy, turning them into sdO-like stars for ~$10^7$ yr. After ~$10^7$ yr, the core helium of He PIRSs should be exhausted, and the stars should evolve to the helium RG phase. The simulations are terminated at ~$10^5$ yr, since the SN Ia remnant may not be recognizable after this time.
Figure 5. Relaxed post-impact companion models in MESA for specific entropy, helium composition (Y), density, temperature, and enclosed luminosity as functions of the fractional mass for models HeWDa, HeWDb, HeWDe, and HeWDe in Table 2.

We have noticed that there is $\lesssim 1\%$ artificial mass loss during angle averaging of the post-impact density, since the helium star is close to the edge of the simulation box at the end of the FLASH simulations. However, the most important factors that control the post-impact evolution are the amount of energy deposited and the corresponding depth, which are mainly concentrated in the outer 5% of mass (see the temperature bump in Figure 4). We have tested the effect of mass loss by changing the mass of the PIRS and conclude that the artificial mass loss will not lead to a notable difference in the post-impact evolution.

The evolutionary tracks of He PIRSs in the H-R diagram are plotted in Figures 8 and 9, representing the effective temperature versus luminosity and effective temperature versus surface gravity, respectively. Based on our post-impact simulations, we predict that He PIRSs will evolve to luminous OB stars on a timescale of $\sim 30$ yr and will fade within a hundred years.

Therefore, only in young SN Ia remnants can one observe luminous helium OB stars at the center of the SNR if the non-degenerate companion was an He star. However, an sdO-like star is observable for the remaining time. Note that for the He-WD channel in the SDS the delay time ($\sim 45$–220 Myr; Wang & Han 2010b) is much shorter than in other SDS channels since the helium star was formed from a more massive star. This suggests that He PIRSs are expected to be detected only in star-forming regions.

As SNe Iax represent a sub-class of sub-luminous SNe Ia, their explosion energy and ejecta speed are lower than in the standard W7 model, causing a reduced effect of the SN impact on binary companions. In Paper III, we studied the effect of the SN explosion energy on the post-impact evolution and found that the explosion energy dramatically affects the amount and depth of SN energy deposition in MS-like PIRSs. For a lower explosion energy, the effect of the SN impact is shallower, causing a shorter radiative diffusion timescale. However, these differences become small once the deposited energy has radiated away. Therefore, for He PIRSs with sub-luminous explosions, He PIRSs behave similarly after $\sim 30$ yr, but with less mass lost during the SN impact.

4.2. Color–Magnitude Diagram

For direct comparison with observations, we convert the luminosity to magnitude in the optical bands. Given the effective temperature ($T_{\text{eff}}$) and photospheric radius ($R$) of a PIRS, the magnitude of the PIRS can be calculated using Equation (4) with an assumption of blackbody radiation:

$$m_{S_{\lambda}} = -2.5 \log_{10} \left[ \int \frac{S_{\lambda}(\tau B_{\lambda}) \, d\lambda}{\int (f_{\nu} \nu^2 \lambda^2 S_{\lambda} \, d\lambda) (\frac{R}{d})^2} \right] ,$$

where $S_{\lambda}$ is the sensitivity function of a given filter at wavelength $\lambda$, $B_{\lambda}$ is the Planck function, $d$ is the distance of the PIRS, and $f_{\nu} = 3.631 \times 10^{-29}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ is the zero-point value in the AB magnitude system. Figure 10 shows the color–magnitude evolutionary trajectories of He PIRSs. The absolute magnitudes are calculated using the broadband $u$ and $v$ filters.
5. DISCUSSION

In this section, we study the possible observational effects of the post-SN-impact evolution. In particular, we examine the effect of nickel contaminations from the SN ejecta on the post-impact evolution. The surface rotational speeds of He PIRSs during post-impact evolution are also predicted as functions of time. Furthermore, we also discuss the possibility that He PIRSs could be a source of single sdO stars and/or HVSs.

Figure 7. Evolution of the photospheric radius, effective temperature, and luminosity as functions of time. Each line shows the evolution of an He PIRS in Table 2.

Figure 8. Evolutionary tracks in the H-R diagram for different He PIRS models. Each line represents an evolutionary track of an He PIRS in Table 2 over an interval of $10^5$ yr. The filled squares indicate the conditions at 0.1 yr after the SN impact; filled stars, 10 yr after the SN impact; filled triangles, $10^2$ yr after the SN impact; filled circles, $10^3$ yr after the SN impact. The He PIRS models with letter “n” represent the cases without nickel contamination (with dashed lines).

(A color version of this figure is available in the online journal.)

Figure 9. Same as Figure 8, but for surface gravity (in cgs units) vs. effective temperature (K).

(A color version of this figure is available in the online journal.)

Figure 10. Same as Figure 8, but for $V$ magnitude vs. $B-V$ color. The magnitudes are absolute magnitudes using the broadband $u$ and $v$ filters in the AB magnitude system.

(A color version of this figure is available in the online journal.)
5.1. Nickel Contamination

The envelope of a companion star could be contaminated by the SN ejecta during the SN impact or as fallback. In Paper II, we have shown that this nickel contamination is much greater for He PIRSs ($1.7 \times 10^{-4} M_\odot$ to $1.5 \times 10^{-3} M_\odot$; see Table 2) than MS-like PIRSs ($<10^{-5} M_\odot$). We note that the nickel contamination can affect the post-impact evolution for He PIRSs, since the change of metallicity in the envelope will also change the opacity and radiative diffusion timescale. To study this effect, two He PIRSs (labeled “HeWDbn” and “HeWDcn”) without nickel contamination have been reconstructed by removing the bound nickel at the end of the FLASH simulations. The hydrostatic profiles of the reconstructed models do not change significantly, but they have slightly smaller radii. Figure 11 shows the evolution of the photospheric radius, effective temperature, and luminosity of these two models with and without (cases with the letter “n”) nickel contamination. Removing the bound nickel causes the opacity to be lower in the outer regions, making stars more transparent and causing smaller photospheric radii. It is clear that the maximum radii of He PIRSs without nickel contamination are much smaller than the same He PIRSs with nickel contamination. Note that we used the fixed metal tables (Type I) opacity module in MESA. Thus, the opacity contributed by heavy metals in our calculations is not very accurate, since the abundance ratios are different in the nickel-contaminated region than the abundances assumed in OPAL. However, the difference between models with and without nickel contamination is not very significant in the H-R diagrams (see Figure 8). Thus, these differences can be treated as an uncertainty in our post-impact simulations.

Energy generation by $^{28}$Ni decay and $^{28}$Co decay in the SN ejecta-contaminated regions is neglected in our calculations. This is justified by the fact that the energy generated by these nuclear decays is much smaller than the energy deposited from the SN ejecta since the mass of bound nickel is small.

5.2. Surface Rotational Speed

In Paper III, we showed that the surface rotational speed could decrease to $\sim 10$–$20$ km s$^{-1}$ for MS-like PIRSs, if the specific angular momentum is conserved during the post-impact evolution. This result implied that the possible PIRS candidate Tycho G could not be completely ruled out because of its low surface rotation speed. Here, we apply the same method to He PIRSs. The He stars were set into rigid rotation at the beginning of the FLASH simulations because the synchronization time due to tidal locking for a given mass ratio $q$ and orbital period $P$ (Zahn 1977), $t_{\text{sync}} \sim 10^4(1 + q)/2q^2 P^4$ yr $\ll$ 1 day, is extremely short in the He-WD channel. After the SN impact, an He PIRS loses $\lesssim 10\%$ of its angular momentum and is no longer in a state of rigid-body rotation. Thus, an angle-averaged, post-impact radial angular velocity profile can be calculated by averaging different latitudes and longitudes in spherical coordinates in the FLASH output. The post-impact surface rotational speed can be calculated by assuming the specific angular momentum to be conserved after the SN impact. Figure 12 shows the post-impact evolution of the surface rotational speed versus evolution time. It is found that the angle-averaged, post-impact radial angular velocity profiles exhibit some variations in the envelope region, and we estimate the uncertainty by using the standard deviation of the specific angular momentum within the envelope. Since He stars are more compact and are closer to the accreting WD at the time of the SN explosion, the surface rotational speed should be much higher than for MS-like companions in the MS-WD channel. The surface rotational speed at the time of the SN Ia explosion could be as high as $\sim 200$ km s$^{-1}$ if the He star companion is close to co-rotation due to tidal locking. For He PIRSs, our calculations show that the surface rotational speed should decrease to $\lesssim 10$ km s$^{-1}$ when the star expands to its maximum size. However, because the radiative diffusion timescale is short, the surface rotational speed is slow only during the first hundred years and will eventually increase to $\sim 100$ km s$^{-1}$ after a few hundred years. Therefore, if He PIRSs exist in historical Ia SNRs, their surface rotation...
rotational speeds could be higher than 50 km s\(^{-1}\), depending on the progenitor models and the ages of the SNR.

5.3. He PIRSs as Hypervelocity Stars?

During the past decade a number of HVSs have been observed in the halo of our Galaxy. They are sub-luminous O- or B-type stars or MS B stars with high radial velocities that could exceed the escape velocity of the Milky Way. The common explanation for their formation involves tidal ejection in binary stars (or triple stars) associated with either a massive black hole or binary black holes (Hills 1988; Yu & Tremaine 2003). Alternatively, Wang & Han (2009) suggest that the surviving He PIRSs in SNe Ia within the He-WD channel could be a source of HVSs. In our calculations, He PIRSs are sdO-like stars for \(\sim 10^7\) yr and thereafter evolve to the helium RG phase. The final linear velocity (original orbital velocity plus kick velocity) of our He PIRSs is \(\sim 400-800\) km s\(^{-1}\) (see Table 2). He PIRSs could move to a distance of \(\sim 10\) kpc within \(10^7\) yr, becoming single sdO-like stars in the halo of our Galaxy, if the Ia SNRs have diffused away at that time. The HVS US 708 (or HS 702) has a radial velocity \(v \sin i = 708 \pm 15\) km s\(^{-1}\), \(T_{\text{eff}} = 44,500\) K, log \(g = 5.23\), and Galactic latitude \(b = +47.05\) at a distance of 19 kpc (Hirsch et al. 2005), giving a displacement of 14 kpc from the Galactic plane. The effective temperature and surface gravity of US 708 are consistent with our He PIRS models, but they require a subdwarf lifetime longer than several times \(10^7\) yr to reach such a distance, if the SN exploded in the Galactic plane. Therefore, a less massive model may better match US 708, since less massive models have higher linear speeds and longer subdwarf lifetimes.

6. CONCLUSIONS

We have investigated the post-impact evolution of He PIRSs within the SDS for SNe Ia via numerical simulations. Four helium-star models from Wang et al. (2009) are considered in our calculations. We performed three-dimensional hydrodynamics simulations using the methods that were described in Paper II. The post-impact evolution of these stars has been studied by reconstructing hydrostatic models based upon the final output in the hydrodynamics simulations and then interpolating them into a one-dimensional stellar evolution code, MESA. It is found that He PIRSs expand dramatically and evolve to become luminous OB stars within about \(\sim 10-30\) yr after the SN Ia explosion. This phase is short (<100 yr), and therefore these luminous OB stars are not likely to be detected in historical Ia SNRs. After \(\sim 30\) yr, He PIRSs contract and evolve into hot blue-subdwarf-like (sdO-like) stars due to the release of gravitational energy. Therefore, we predict that most He PIRSs should be sdO-like stars and could be detectable in nearby Ia SNRs.

We also predict that these He PIRSs should be rapidly rotating \((v_{\text{rot}} \gtrsim 50\) km s\(^{-1}\)). Although a few fast rotating hot blue subdwarfs have been observed recently (Geier et al. 2011, 2013), most single hot blue subdwarfs (sdOs and sdBs) are slowly rotating (Geier & Heber 2012). If single hot blue subdwarfs originate from the merger of two He WDs (sdOs/sdBs; Heber 2009), merger via a common envelope phase on the RG branch (Politano et al. 2008), or the He-WD channel in SNe Ia (sdOs), the theoretical predictions cannot explain these observations, suggesting that other mechanisms operate to slow down the rotation, such as magnetic braking.

The He-WD binary channel is favored for the prompt DTD in the SDS and is expected to occur in star-forming regions. Since the orbital period immediately prior to the SN Ia explosion in the He-WD channel is extremely short \((\lesssim 1\) yr), the system is expected to be tidally locked. Thus, He stars should be rapidly rotating at the time of the SN Ia explosion. Although some angular momentum will be lost during the SN impact, He PIRSs are still expected to be rapidly rotating after \(\sim 30\) yr. The spatial velocity of He PIRSs is also expected to be high, reflecting the high orbital speed at the time of the SN Ia explosion and implying that He PIRSs could contribute to the HVS population (i.e., US 708).

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Figure 12. Evolution of surface rotational speed for all He-WD models in Table 2. The error is estimated using the variation of specific angular momentum within the envelope of initial hydrostatic solutions (see Section 5.2 for detailed description). The number of error bars is only chosen for visualization and does not represent the actual number of data points.

(A color version of this figure is available in the online journal.)
