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PRE-EXPLOSION COMPANION STARS IN TYPE Iax SUPERNOVAE

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ABSTRACT

Type Iax supernovae (SNe Iax) are proposed as one new sub-class of SNe Ia since they present observational properties that are sufficiently distinct from the bulk of SNe Ia. SNe Iax are the most common of all types of peculiar SNe by both number and rate, with an estimated rate of occurrence of about 5%–30% of the total SN Ia rate. However, the progenitor systems of SNe Iax are still uncertain. Analyzing pre-explosion images at SN Iax positions provides a direct way to place strong constraints on the nature of progenitor systems of SNe Iax. In this work, we predict pre-explosion properties of binary companion stars in a variety of potential progenitor systems by performing detailed binary evolution calculations with the one-dimensional stellar evolution code STARS. This will be helpful for constraining progenitor systems of SNe Iax from their pre-explosion observations. With our binary evolution calculations, it is found that the non-degenerate helium (He) companion star to both a massive C/O WD ($>1.1\ M_{\odot}$) and a hybrid C/O/Ne WD can provide an explanation for the observations of SN 2012Z-S1, but the hybrid WD+He star scenario is more favorable.

Key words: binaries: close – supernovae: general

1. INTRODUCTION

Type Iax supernovae (SNe Iax) were recently proposed as one of the largest classes of peculiar SNe (Foley et al. 2013). Members of this subclass, have several observational similarities to normal SNe Ia (Li et al. 2003; Branch et al. 2004; Jha et al. 2006; Phillips et al. 2007; Foley et al. 2009, 2010, 2013), but also present sufficiently distinct observational properties. SNe Iax are significantly fainter than normal SNe Ia (Foley et al. 2013, 2014). They have a wide range of explosion energies (10^{49}–10^{51} erg), ejecta masses (0.15–0.5 $M_{\odot}$), and ^{56}Ni masses (0.003–0.3 $M_{\odot}$). The spectra of SNe Iax are characterized by lower expansion velocities (2000–8000 km s^{-1}) than those of normal SNe Ia (15,000 km s^{-1}) at similar epochs. Moreover, two SNe Iax (SN 2004cs and SN 2007J) were identified with strong He lines in their spectra (Foley et al. 2009, 2013).

SNe Iax are the most common of all types of peculiar SNe by both number and rate, with an estimated rate of occurrence of about 5%–30% of the total SN Ia rate (Li et al. 2011; Foley et al. 2013). Most SNe Iax are observed in late-type, star-forming galaxies (Foley et al. 2013; Lyman et al. 2013; White et al. 2015). The observational constraints suggest relatively short delay times for the progenitor systems of SNe Iax (<500 Myr, see Foley et al. 2014). However, there is at least one Iax event, SN 2008ge, that was observed in an S0 galaxy with no signs of star formation (which suggests a long delay time, see Foley et al. 2010, 2013).

It is accepted that SNe Iax are either thermonuclear explosions of accreting WDs or the core-collapse of massive stars. However, the nature of the progenitor systems that give rise to SNe Iax has not been yet elucidated (Foley et al. 2013, 2014; Liu et al. 2013a, 2015; McCully et al. 2014; Fisher & Jumperx 2015). Given the diversity of SNe Iax, multiple different progenitor channels are likely to contribute to the observed population. The most likely progenitor scenarios currently proposed for SNe Iax are summarized as follows.

1. The Chandrasekhar-mass (Ch-mass) scenario. A WD accretes hydrogen (H)- or helium (He)-rich material from a non-degenerate companion until its mass approaches the Ch-mass, $M_{\rm Ch} \approx 1.4\ M_{\odot}$, at which point a thermonuclear explosion ensues (Whelan & Iben 1973; Nomoto 1982; Nomoto et al. 1984). Here, the companion star could be a H-rich donor (either a main-sequence; MS star, a subgiant, or a red giant; RG) or a He-rich donor (He star). It has been suggested that a Ch-mass WD can undergo either a deflagration, or a detonation, or a delayed detonation to lead to an SN Ia explosion (Arnett 1969; Woosley et al. 1986; Khokhlov 1989). In this work, we only focus on SNe Iax that were recently thought to likely be produced from the deflagration explosion of a WD. Turbulent deflagrations in WDs can cause strong mixing of the SN ejecta (e.g., Röpke 2005), and the small amount of kinetic energy released from deflagration explosions is in good agreement with the low expansion velocities of SNe Iax (Foley et al. 2013). Furthermore, the (weak) pure deflagration explosion of a Ch-mass WD has recently been proposed as a promising scenario for SNe Iax (Kromer et al. 2013, 2015; Fink et al. 2014). In this specific deflagration explosion scenario, a weak deflagration explosion fails to explode the entire WD, leaving behind a polluted WD remnant star (Jordan et al. 2012; Kromer et al. 2013; Fink et al. 2014). Hydrodynamical simulations have shown that the off-center-ignited weak deflagrations of Ch-mass C/O or hybrid C/O/Ne WDs (García-Berro et al. 1997; Chen et al. 2014; Denissenkov et al. 2015) are able to reproduce the characteristic observational features of SNe Iax quite well (Jordan et al. 2012; Kromer et al. 2013, 2015; Fink et al. 2014), including the faint 2008ha-like SNe Iax (Kromer et al. 2015). However, it is impossible to determine the exact ignition condition of a Ch-mass WD in this work because the WD is treated as a point mass in our binary calculations (see Section 2). We therefore assume that all Ch-mass WDs in our binary calculations will lead to (weak) pure deflagration explosions for SNe Iax.

In addition, the pulsational delayed detonation explosion of a near Ch-mass WD has been proposed to be a possible scenario for the SN Iax SN 2012Z (Stritzinger et al. 2014) which has been suggested to come from a progenitor system consisting of a He-star donor and a C/O WD (McCully et al. 2014). However, further and more detailed hydrodynamic and radiative-transfer simulations for this pulsational delayed detonation explosion model are still needed.

2. *The sub-Ch-mass scenario* (e.g., Iben et al. 1987; Livne 1990; Woosley & Weaver 1994; Woosley & Kasen 2011). The WD accretes He-rich material from a companion star (a non-degenerate He star or a He WD) to accumulate a He-layer on its surface. If a He-shell accumulation reaches a critical value ($\simeq$0.02–0.2 $M_{\odot}$), a single-detonation (i.e., ".Ia model," see Bildsten et al. 2007; Shen et al. 2010) or double-detonation is triggered to cause the thermonuclear explosion of the sub-Ch-mass WD. However, current works show that theoretical spectra and light-curves predicted from the simulations with a thick He shell (0.1–0.2 $M_{\odot}$) do not match the observations of SNe Ia/Iax (Kromer et al. 2010; Woosley & Kasen 2011; Sim et al. 2012). Therefore, we will assume a thin He shell ($\approx$0.05 $M_{\odot}$) in our subsequent calculations for the sub-Ch-mass scenario. Recent population synthesis calculations for the sub-Ch-mass double-detonation scenario suggest that the rates and delay-time distribution from this scenario seem to be consistent with the observations of SNe Iax (Ruiter et al. 2011; Wang et al. 2013). However, current explosion models for the double-detonation scenario (Bildsten et al. 2007; Fink et al. 2010; Kromer et al. 2010; Sim et al. 2010; Shen et al. 2010; Woosley & Kasen 2011) show that this kind of explosion struggles to reproduce the characteristic features of SNe Iax, for example, the low ejecta velocity of SNe Iax, low ^{56}Ni mass, and strong mixing of their explosion ejecta. Also, the sub-Ch-mass explosions are not going to undergo a weak pure deflagration as in the case for Ch-mass WDs. Nevertheless, further investigations are still required and numerous complications remain to be solved in such a model (Piersanti et al. 2014; Shen & Moore 2014; Piro 2015). For instance, Piro (2015) suggests that including turbulent mixing in He-accreting WDs can lead to more than 50% C/O in the accreted layer at the time of ignition, which probably causes the nucleosynthetic products to be different, or similar. It is unclear if any extended explosion model within this scenario can successfully reproduce most observational features of the least luminous SNe Iax. We therefore also include the sub-Ch-mass explosion as a potential scenario for producing SNe Iax in our presented calculations.

3. *The massive-star core-collapse scenario* (e.g., Umeda & Nomoto 2005; Valenti et al. 2008; Moriya et al. 2010). A core-collapse SN is triggered by the gravitational collapse of the Fe core of a massive star (with an initial MS mass above about 10 $M_{\odot}$. that had its H and a significant amount of He stripped from its outer layers. In particular, the fallback core-collapse explosions of massive stars have been proposed to explain the peculiar SN Iax SN 2008ha because these specific SN explosions could produce a low explosion energy and ^{56}Ni mass to account for the properties of SN 2008ha (Moriya et al. 2010). However, this core-collapse scenario seems difficult to explain the full diversity of SNe Iax. Also, a TP-AGB-like source at the position of SN 2008ha has been detected by a recent *Hubble Space Telescope (HST)* analysis (Foley et al. 2014). This source has been further suggested to be a candidate of either the bound remnant of the WD, or the companion star of the WD, or the companion of the massive-star progenitor (although it is very unlikely, see Foley et al. 2014). If future observations confirm that this source is indeed a bound remnant of the WD, a massive star as the progenitor of SN 2008ha would be ruled out. Also, pre-explosion imaging for another SN Iax, SN 2008ge, has ruled out particularly massive stars as potential progenitors (Foley et al. 2010, 2015).

Analyzing pre-explosion images at the SN position provides a direct way to constrain SN progenitor systems (e.g., see Foley et al. 2014, 2015; McCully et al. 2014). To date, no progenitors of normal SNe Ia have yet been directly observed, even for detections of relatively nearby SNe Ia, SN 2011fe, and SN 2014J. However, the probable progenitor system of an SN Iax SN 2012Z (i.e., SN 2012Z-S1) has been recently discovered from pre-explosion *HST* images (McCully et al. 2014). It is further suggested that SN 2012Z had a progenitor system consisting of a He star donor and a C/O WD (McCully et al. 2014).

In the accreting-WD explosion scenario, the WD can only be observed directly in our own Milky Way and several very nearby galaxies because the WD would be faint. Consequently, the companion stars generally play a major role in determining the pre-explosion signatures of progenitor systems. It may be possible to determine the nature of the companion star of SNe Iax, and thus their progenitors, by analyzing pre-explosion images at the SN positions. In this work, we predict pre-explosion signatures of companion stars for different progenitor systems that have been recently proposed for SNe Iax. This will be very helpful for analyzing future pre-explosion observations of SNe Iax. In Section 2, we describe the numerical method we used in this work. The pre-explosion signatures of companion stars are presented in Section 3. A comparison between our results and the observation of SN 2012Z-S1 are presented in Section 4. The conclusions are summarized in Section 5.

2. NUMERICAL METHOD AND MODELS

We use the Cambridge stellar evolution code `STARS`, which was originally written by Eggleton (1971, 1972, 1973) and then updated several times (Han et al. 2000). The detailed description of the version we used can be found in Han et al. (2000) and Han & Podsiadlowski (2004). Generally, Roche-lobe overflow (RLOF) is treated by the prescription of Han et al. (2000). All of our stars have metallicity $Z = 0.02$ and start in circular orbits. For H-rich stars (MS, subgiant, and RG), we set the ratio of the typical mixing length (l) to the local pressure scale height (H_P), $\alpha = l/H_P = 2.0$, and the convective overshooting parameter, $\delta_{ov} = 0.12$, which roughly corresponds to an overshooting length of $\approx$0.25 H_P. The He-rich star is evolved without enhanced mixing, i.e., the convective overshooting parameter, $\delta_{ov} = 0$.

In our binary evolution calculations, the accreting WDs (i.e., C/O WDs or hybrid C/O/Ne WDs) are treated as a point mass, only detailed structures of the mass donor stars are solved in the code. We trace detailed mass-transfer of the binary systems until the WDs increase their mass to the critical limit (assuming SN Iax explosions occur). For different companion star models, the mass-growth rate of the WD, $\dot{M}_{WD}$, is defined as follows.

For the H-rich donor star channel, the mass growth rate of the WD, $\dot{M}_{\rm WD} = \eta_{\rm He}\dot{M}_{\rm He} = \eta_{\rm He}\eta_{\rm H}|\dot{M}_{\rm tr}|$, where $\dot{M}_{\rm He}$ is the mass-growth rate of the He layer under the H-shell burning, and $|\dot{M}_{\rm tr}|$ is the mass-transfer rate from the non-degenerate H-rich companion star. Also, $\eta_{\rm He}$ is the mass-accumulation efficiency for He-shell flashes, which is shown below in detail (see also Kato & Hachisu 2004), and $\eta_{\rm H}$ is the mass-accumulation efficiency for H burning, which is defined as follows (see also Liu et al. 2015)[4]

$$\eta_{\rm H} = \begin{cases} \dot{M}_{\rm cr,H}/\left|\dot{M}_{\rm tr}\right|, & \left|\dot{M}_{\rm tr}\right| > \dot{M}_{\rm cr,H}, \\ 1, & \dot{M}_{\rm cr,H} \geqslant |\dot{M}_{\rm tr}| \geqslant \frac{1}{8}\dot{M}_{\rm cr,H}, \\ 0, & |\dot{M}_{\rm tr}| < \frac{1}{8}\dot{M}_{\rm cr,H}, \end{cases} \quad (1)$$

where $\dot{M}_{\rm cr,H} = 5.0 \times 10^{-7}(1.7/X - 1)(M_{\rm WD}/M_\odot - 0.4)M_\odot\,{\rm yr}^{-1}$ is the critical accretion rate for stable H burning, X is the H mass fraction, $M_{\rm WD}$ the mass of the accreting WD. Here, the optically thick wind (Hachisu et al. 1996) is assumed to blow off all unprocessed material if $|\dot{M}_{\rm tr}|$ is greater than $\dot{M}_{\rm cr,H}$, and the lost material is assumed to take away the specific orbital angular momentum of the accreting WD. The effect of magnetic braking is also included by adopting the description of angular-momentum loss from Sills et al. (2000). If the C/O WD increases its mass to near the Ch-mass limit ($\approx 1.4\,M_\odot$), we assume the SN Iax explosion ensues.

Very recently, considering the uncertainties of the C-burning rate, Chen et al. (2014) have suggested that hybrid C/O/Ne WDs as massive as $1.3\,M_\odot$ can be formed if the convective undershooting of the C-burning layer is large enough and the carbon fraction below the flame is largely reduced. These hybrid C/O/Ne WDs in close binary systems can eventually accrete H- or He-rich material from their companion stars to reach the Ch-mass limit and explode as faint SNe (see García-Berro et al. 1997; Chen et al. 2014; Denissenkov et al. 2015). In this work, this hybrid WD scenario has also been included in our detailed binary evolution calculations for the Ch-mass scenario. Because all WDs are treated as a point mass in our calculations, the C/O WD and the hybrid WD channel are distinguished just based on their initial WD mass (see Section 4). The initial WD masses of $M^i_{WD} = 0.65$, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, and $1.3\,M_\odot$ are considered for the H-accreting Ch-mass scenario (see also Liu et al. 2015). With a low initial WD mass of $0.65\,M_\odot$, only two systems (out of about 120 binary systems that are calculated) can lead to SN Iax explosions, $0.65\,M_\odot$ is thus set to be the minimum WD mass for producing SNe Iax from this channel. A WD mass of $1.3\,M_\odot$ is the maximum initial mass we assumed for a hybrid C/O/Ne WD (see Chen et al. 2014; Denissenkov et al. 2015).

For the He-rich donor star channel, the mass growth rate of the WD, $\dot{M}_{\rm WD} = \eta_{\rm He}|\dot{M}'_{\rm tr}|$ (see also Wang et al. 2010; Liu et al. 2015), where $|\dot{M}'_{\rm tr}|$ is the mass-transfer rate from the He-rich companion star, the $\eta_{\rm He}$ is the mass-accumulation efficiency for He burning, which is set to be

$$\eta_{\rm He} = \begin{cases} \dot{M}_{\rm cr,He}/\left|\dot{M}'_{\rm tr}\right|, & \left|\dot{M}'_{\rm tr}\right| > \dot{M}_{\rm cr,He}, \\ 1, & \dot{M}_{\rm cr,H} \geqslant \left|\dot{M}'_{\rm tr}\right| \geqslant \dot{M}_{\rm st}, \\ \eta'_{\rm He}, & \dot{M}_{\rm st} \geqslant |\dot{M}'_{\rm tr}| \geqslant \dot{M}_{\rm low}, \\ 1\,(\text{no burning}), & |\dot{M}'_{\rm tr}| < \dot{M}_{\rm low}, \end{cases} \quad (2)$$

where $\dot{M}_{\rm cr,He} = 7.2 \times 10^{-6}(M_{\rm WD}/M_\odot - 0.6)M_\odot\,{\rm yr}^{-1}$ is the critical accretion rate for stable He burning; $\dot{M}_{\rm st}$ is the minimum accretion rate for stable He-shell burning (Kato & Hachisu 2004; Piersanti et al. 2014); $\dot{M}_{\rm low} = 4 \times 10^{-8}\,M_\odot\,{\rm yr}^{-1}$ is the minimum accretion rate for weak He-shell flashes (Woosley et al. 1986); $\eta'_{\rm He}$ is obtained from linearly interpolated from a grid computed by Kato & Hachisu (2004). As mentioned above, if the WD increases its mass to the near Ch-mass limit ($\approx 1.4\,M_\odot$), we assume the SN explosion ensues. Here, the initial WD masses of $M^i_{\rm WD} = 0.865$, 0.9, 1.0, 1.1, 1.2, and $1.3\,M_\odot$ are considered for the He-accreting Ch-mass scenario (see also Wang et al. 2010; Liu et al. 2015). The lower mass limit of $0.865\,M_\odot$ is corresponding to the minimum WD mass for producing SNe Iax from this channel, and an upper-limit of $1.3\,M_\odot$ is the maximum initial mass we assumed for the hybrid C/O/Ne WD (see Chen et al. 2014; Denissenkov et al. 2015).

For the low mass-transfer-rate He-accreting case, $|\dot{M}'_{\rm tr}| \lesssim 4 \times 10^{-8}\,M_\odot\,{\rm yr}^{-1}$, a thick layer of helium is believed to grow on the surface of the WD. As a result, once a He-shell accumulation reaches a critical value ($0.05\,M_\odot$ is adopted in this work, see Woosley & Kasen 2011), we assume that a single detonation or double detonation is triggered, the sub-Ch-mass WD explodes as an SN Iax. When the mass-transfer rate is low, $|\dot{M}'_{\rm tr}| \lesssim 1 \times 10^{-9}\,M_\odot\,{\rm yr}^{-1}$, it is suggested that the flash when the He layer ignites is too weak to initiate a carbon detonation, which results in only a single He detonation wave propagating outward (Nomoto 1982). We do not especially distinguish this low-mass-transfer case in our binary evolution calculations because the condition of He ignition is still uncertain (Bildsten et al. 2007; Shen et al. 2010; Woosley & Kasen 2011; Shen & Moore 2014). This is different from the setup in Wang et al. (2013) who did not include the case of $|\dot{M}'_{\rm tr}| \lesssim 1 \times 10^{-9}\,M_\odot\,{\rm yr}^{-1}$ because they only focused on the double-detonation explosions. In the present work, the initial WD masses of $M^i_{\rm WD} = 0.8$, 0.9, 1.0, and $1.1\,M_\odot$ are adopted for the He-accreting sub-Ch-mass scenario. Here, $0.8\,M_\odot$ corresponds to the prediction for the minimum WD mass for carbon burning from recent hydrodynamic simulations. The detonation of a C/O WD may not be triggered for lower mass (Sim et al. 2012). We also expect that the initial C/O WD masses are below $\simeq 1.1\,M_\odot$ as more massive WDs are usually formed consisting of O and Ne, i.e., ONe WDs (Siess 2006; Doherty et al. 2015, but see Ruiter et al. 2013).

In the He-accreting sub-Ch-mass scenario, the companion star could also be a He WD. However, the long delay times of the He-WD donor channel ($\gtrsim$800 Myr, see Ruiter et al. 2011) are inconsistent with the observational constraints on the ages of SN Iax progenitors (<500 Myr; Foley et al. 2013; Lyman et al. 2013; White et al. 2015), and this channel is generally proposed to produce calcium-rich SNe such as SN 2005E

[4] Here, the effect of the accretion disk around a WD is not considered because whether a disk instability occurs or not during the WD-accreting process is unclear (see Hachisu et al. 2010; Kato & Hachisu 2012).

(Foley 2015). Therefore, the He-WD donor scenario is not addressed in our calculations.

3. PRE-EXPLOSION COMPANION STARS

Using the method described in Section 2, we performed detailed calculations for a set of binary systems with various initial WD masses ($M^i_{\rm WD}$), companion masses (M^i_2), and orbital periods (P^i) in different progenitor scenarios. Consequently, the range of companion stars of progenitor properties at the moment of SN Iax explosions, e.g., the bolometric luminosity (L), effective temperature ($T_{\rm eff}$), photospheric radius (R), orbital velocity ($V_{\rm orb}$), and surface gravity (g) are directly determined in our binary calculations with the STARS code. In addition, some properties of binary progenitor systems when the SN explosion occurs can also be calculated, e.g., the orbital periods of binary systems, the amount of mass lost during the optically thick stellar wind phase, mass-transfer rate at the moment of SN explosion, and even equatorial rotational velocities of companion stars (if we assume that the companion stars co-rotate with their orbits). All of these pre-explosion signatures of companion stars and binary progenitors can be compared with pre-explosion observations of SNe Iax to help understand the nature of the SN Iax progenitor (e.g., McCully et al. 2014).

Furthermore, to facilitate direct comparison with optical observations, the bolometric luminosity is converted to broadband magnitudes by using the same method as Pan et al. (2013) under the assumption that the companion photosphere emits a blackbody radiation spectrum:

$$m_{S_\lambda} = -2.5\ \log_{10}\left[\frac{\int S_\lambda(\pi B_\lambda)d\lambda}{\int \left(f_\nu^{\,0}\ c/\lambda^2\right)S_\lambda d\lambda}\ \left(\frac{R}{d}\right)^2\right], \qquad (3)$$

where S_λ is the sensitivity function of a given filter at wavelength λ, B_λ is the Planck function, d is the distance of the star, and $f_\nu^0 = 3.631 \times 10^{-20}\,{\rm erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}$ is the zero-point value in the AB magnitude system. Here, the effective temperature ($T_{\rm eff}$) and photospheric radius (R) of a pre-explosion companion star obtained from our binary evolution calculations are needed. Specifically for this work, the different filters of the *HST*/WFC3 system and their corresponding sensitivity functions are considered in this study. The absolute magnitudes are calculated in the *AB* magnitude system.

Figure 1 illustrates the Hertzsprung–Russell (H–R) diagram in different representations using the *HST* wavebands. As it is shown, companion stars in the H-rich donor and He-rich donor channel are independently located in the H–R diagram at the moment of SN explosion. We can also clearly distinguish the location of companion stars between the He-rich donor Ch-mass channel (i.e., C/O WD+He star and hybrid WD+He star channel) and the He-rich donor sub-Ch-mass channel. This indicates that we can probably rule out (or confirm) the proposed progenitor scenarios for SNe Iax with pre-explosion observations at the SN Iax position. But, unfortunately, we cannot fully distinguish the hybrid C/O/Ne WDs' companions and C/O WDs' companions in the Ch-mass explosion scenarios because the accreting WDs are treated as a point in our detailed binary evolution calculations (but see the discussion in Section 4).

4. COMPARISON WITH SN 2012Z

Recently, a luminous blue source (SN 2012Z-S1) was detected in pre-explosion *HST* images that was coincident with the location of SN 2012Z McCully et al. (2014), and the non-degenerate He companion star to a C/O WD (originally proposed for SNe Iax by Foley et al. 2013) was suggested to be the likely explanation of the observations (McCully et al. 2014). However, they also suggested that the possibility of a massive star and an accretion disk around the exploding WD cannot still be excluded (see Figure 2 of McCully et al. 2014). Here, we compare our model results with the observations of SN 2012Z-S1.

4.1. Comparison with Detailed Binary Calculations

A comparison between the results of our binary evolution calculations for different potential progenitor channels and the observations of SN 2012Z-S1 are displayed in Figure 1. As shown in this figure, the predictions from the Ch-mass scenario with a He star donor are consistent with the observations, which agrees with the previous suggestion for the progenitor system of SN 2012Z (see McCully et al. 2014).

However, as previously mentioned, it is impossible to distinguish the C/O WDs and the hybrid WDs in our binary calculations because the accreting WD is set up as a point mass. To further discuss the differences of companion stars in the C/O WD+He star and hybrid WD+He star channel, we simply assume the range of initial WD mass for the C/O WD+He star channel of 0.865–1.2 $M_\odot$, the range of initial WD mass for the hybrid WD+He star channel of 1.1–1.3 $M_\odot$ (left column of Figure 2, see also Chen et al. 2014; Denissenkov et al. 2015). In Section 4.2, our binary population synthesis (BPS) calculations for the hybrid WD+He star channel will obtain that most binary systems in this channel have an initial WD mass larger than 1.1 $M_\odot$, the binary systems with a lower initial WD mass are quite rare. In addition, only a few C/O WDs are formed with a mass exceeding 1.1 $M_\odot$. This implies that our assumptions on the initial masses of C/O WDs and hybrid WDs are appropriate.

The left column in Figure 2 shows the locations of companion stars at the moment of SN explosions for the C/O WD+He star and hybrid WD+He star Ch-mass scenario, respectively. It is shown that the observation of SN 2012Z-S1 is only consistent with the predicted companion locations from the hybrid WD+He star scenario and the C/O WD+He star scenario with an initial C/O WD mass of 1.2 $M_\odot$. Taking the problem of the origin of very massive C/O WDs into account, our detailed binary evolution calculations seem to disfavor that SN 2012Z-S1 is a non-degenerate companion star to a C/O WD, it is more likely to be a He star with a hybrid C/O/Ne WD. Because the hybrid WDs have much lower C to O abundance ratios at the moment of the explosive C ignition than their pure C/O counterparts (Denissenkov et al. 2015), which probably lead to different observational characteristics from those of the Ch-mass C/O WDs after the SN explosions and thus being distinguished by spectroscopy observations. Recently, an off-center deflagration in a near Ch-mass hybrid C/O/Ne WD has been simulated by Kromer et al. (2015). This showed that deflagrations in near Ch-mass hybrid C/O/Ne WDs can explain the faint SN Iax SN 2008ha (Kromer et al. 2015). However, only a simple near Ch-mass hybrid C/O/Ne WD model was used, more future works with considering different initial

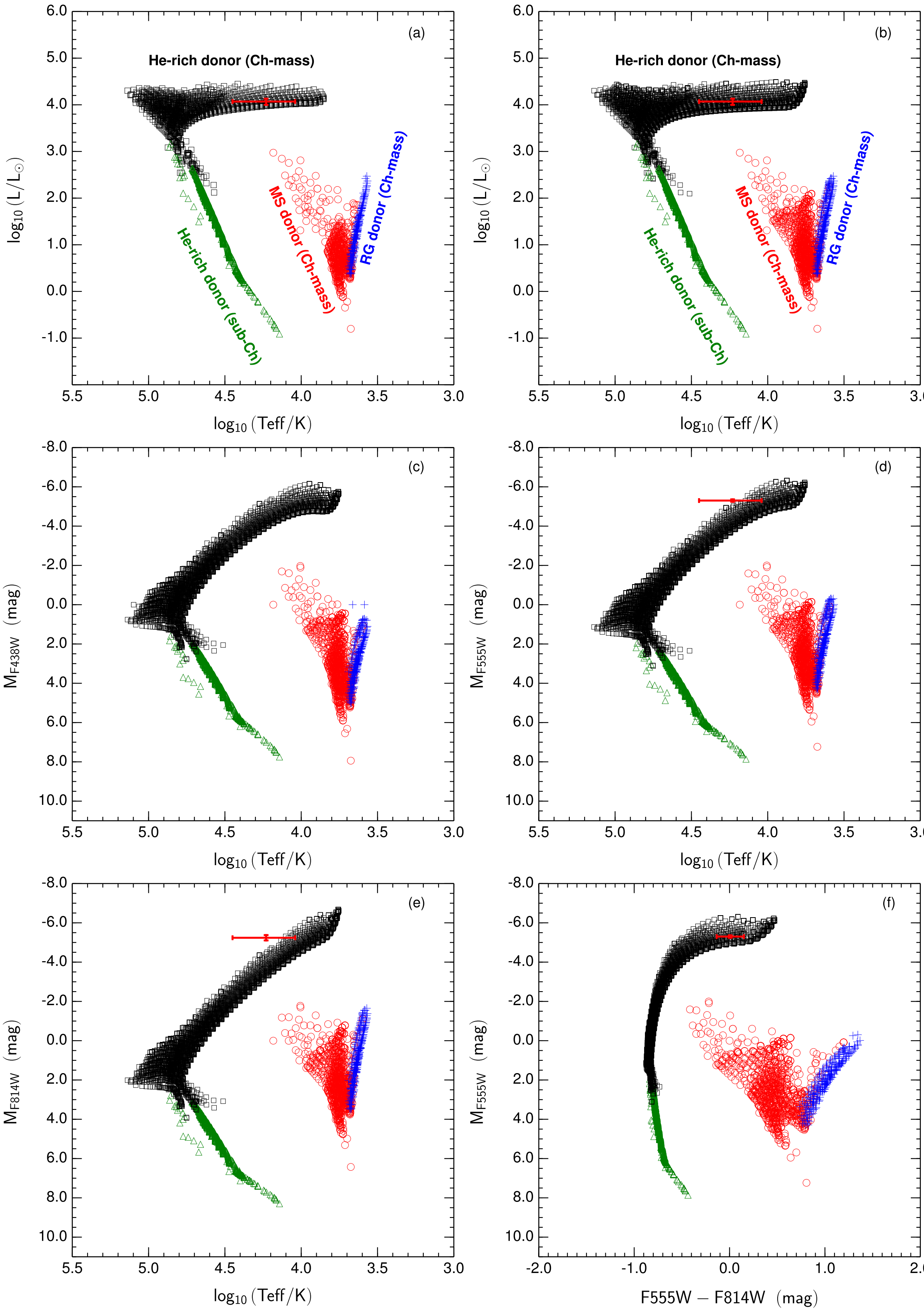

Figure 1. Panel (a): H–R diagram of pre-explosion companions of SNe Iax in different progenitor scenarios. In this panel, initial masses of WDs in the Ch-mass scenario up to a maximum value of 1.2 $M_{\odot}$. Panel (b): similar to panel (a), but 1.3 $M_{\odot}$ initial mass WDs are also included for the H/He-rich accreting Ch-mass scenario. Panels (c), (d), and (e): similar to panel (b), but for different *HST*/WFC3 band magnitude vs. effective temperature. Panel (f): similar to panel (b), but for color–magnitude diagram ($M_{\mathrm{F555W}} - M_{\mathrm{F814W}}$, M_{F555W}). The red error bar shows the *HST* observation of the SN 2012Z-S1 of McCully et al. (2014). The red circle, blue cross, and black square symbols corresponding to the MS, RG, and He star donor Ch-mass channel. The green triangle symbols represent the sub-Ch-mass channel.

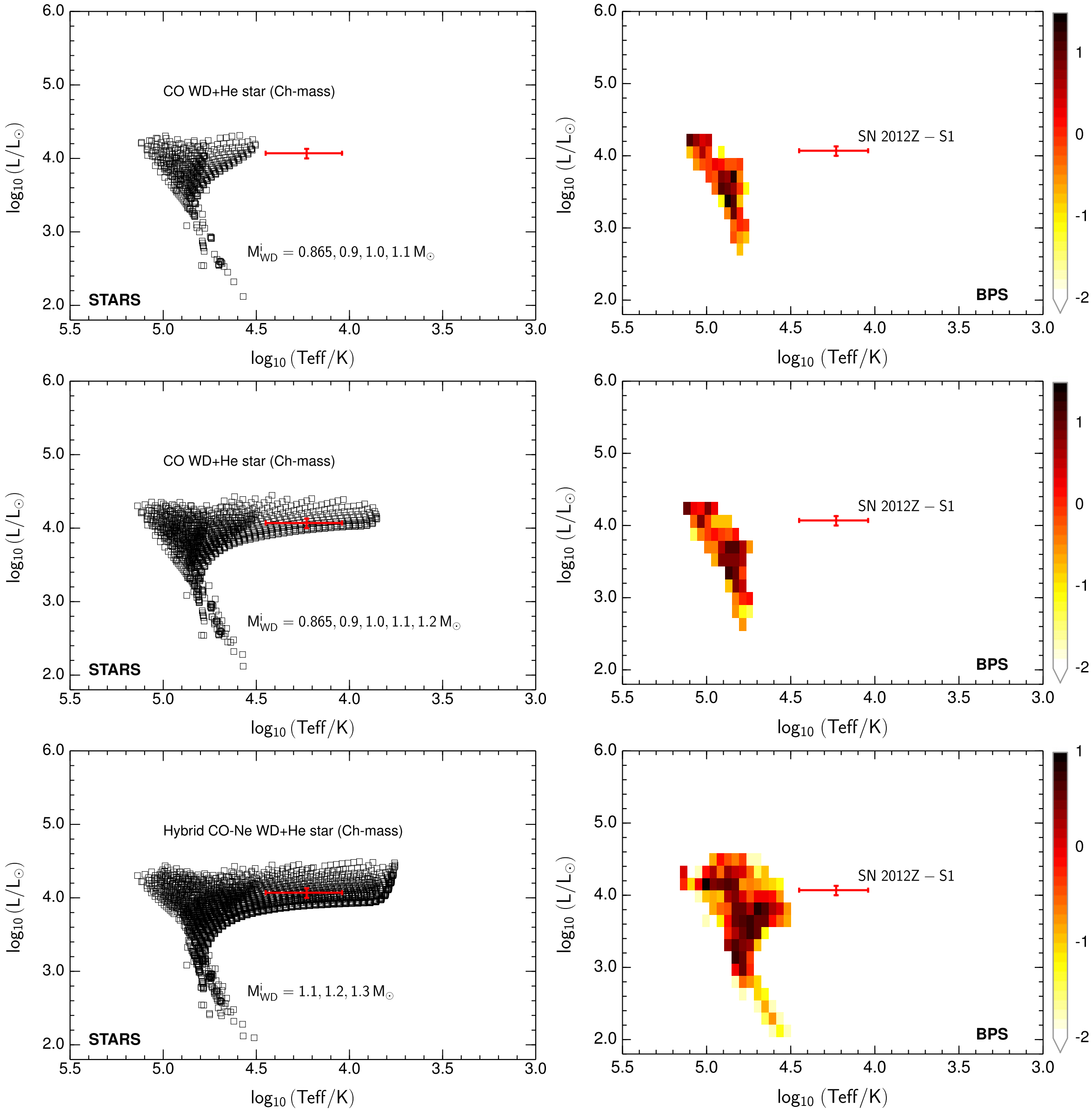

Figure 2. Left column: similar to panel (b) of Figure 1, but only for the He-star donor Ch-mass scenario. Right column: the distributions (in logarithmic scale) of companion stars in the the plane of ($\log_{10} T_{\rm eff}$, $\log_{10} L$), which are obtained from BPS calculations assuming a constant star formation rate of 3.5 $M_\odot$ yr^{-1}. Here, the C/O WD+He star (top + middle row) and hybrid C/O/Ne WD+He star (bottom row) Ch-mass channel are considered, respectively. To better compare with the observation of the SN 2012Z-S1 (the error in red, see McCully et al. 2014), we show the results from the C/O WD+He star channel by including (middle row) or excluding (top row) the calculations with an initial WD mass of 1.2 $M_\odot$.

conditions are needed to explore the deflagration explosions of hybrid WDs.

4.2. Comparison with BPS Calculations

Furthermore, to obtain the distributions of properties of companion stars of C/O WD (or hybrid C/O/Ne WD) + He-star Ch-mass scenario at the moment of SN explosion, we have performed a detailed Monte Carlo simulation with a rapid population synthesis code (Hurley et al. 2000, 2002). The code follows the evolution of binaries with their properties being recorded at every step. If a binary system evolves to a C/O WD (or hybrid C/O/Ne WD) + He-star system, and if the system, at the beginning of the RLOF phase, is located in the SN Ia production regions in the plane of ($\log_{10} P^i$, M_2^i) for its $M^i_{\rm WD}$, where P^i, M_2^i and $M^i_{\rm WD}$ are, respectively, the orbital period, the secondary mass, and the WD's mass of the C/O WD (or hybrid C/O/Ne WD) + He-star system at the beginning of the RLOF, we assume that an SN Ia is resulted, and the properties of the WD binary at the moment of SN explosion are obtained by interpolation in the three-dimensional grid ($M^i_{\rm WD}$, M_2^i, $\log_{10} P^i$) of the close WD binaries obtained in our detailed binary evolution calculations. We refer to Han & Podsiadlowski (2004) and Liu et al. (2015) for a detailed description about the BPS method used here.

The initial mass function of Miller & Scalo (1979) is used in this work. We assumed a circular binary orbit and set up a constant initial mass ratio distribution (i.e., $n(q') =$ constant, see Duchêne & Kraus 2013). We assumed a constant star formation rate (SFR) of 3.5 $M_\odot$ yr^{-1}. The standard energy equations of Webbink (1984) were used to calculate the output of the common envelope (CE) phase. Similar to our previous studies (e.g., Wang et al. 2010; Liu et al. 2015), we use a single free parameter $\alpha_{\rm CE}\lambda$ to describe the CE ejection process, and we set $\alpha_{\rm CE}\lambda = 1.5$. Here, $\alpha_{\rm CE}$ is the CE ejection efficiency, i.e., the fraction of the released orbital energy used to eject the CE; λ is a structure parameter that depends on the evolutionary stage of the donor star. Specifically, for the hybrid WDs+He star channel, another parameter of the uncertainty of the carbon burning rate (see Chen et al. 2014) is introduced and it is set to 0.1 (see also Wang et al. 2014).

The distributions of companion-star temperatures and luminosities at the moment of SN Iax explosion from our BPS calculations for the C/O WD+He star and hybrid WD+He star scenario are shown in Figure 2 (right column). If we assume the initial maximum C/O WD mass is 1.1 $M_{\odot}$, we cannot obtain companion stars as cool as SN 2012Z-S1 in both our detailed binary calculations and BPS calculations. In addition, although SN 2012Z-S1 lies in the regions that can potentially be reached by our detailed binary simulations for the 1.2 $M_{\odot}$ C/O WD+He star model (middle row in Figure 2) and for the hybrid WD+He star model (bottom row in Figure 2), SN 2012Z-S1 is still much cooler than predictions from our BPS calculations. In fact, no star has been obtained from our BPS calculations that lies in the region of the location of SN 2012Z-S1. We have also studied how the different CE efficiencies affect the results. Even if various CE efficiencies (i.e., different values of $\alpha_{\rm CE}\lambda = 0.5$–$1.5$) are adopted, we still cannot obtain the stars as cool as SN 2012Z-S1. However, we caution that BPS calculations still have some uncertainties (see below). Also, Figure 2 shows that our detailed binary calculations can significantly contribute to the number of systems in the vicinity of SN 2012Z. The discrepancy between the STARS results and the BPS predictions is because we do not consider the detailed formation channels of WD+He star binary systems in our binary calculations with the STARS code. To obtain a star as cool as SN 2012Z-S1 at the moment of SN Iax explosion, relatively wide WD+He star binary systems with an orbital period of $\gtrsim$10 days are needed. However, such wide WD+He star binary systems cannot be produced by our BPS calculations. Here, the initial conditions of the populations and the treatment of the physics of binary evolution are considered as reasonable as possible in our BPS studies based on current observations and theoretical models (e.g., see Duchêne & Kraus 2013). If future observations indeed confirm that SN 2012Z had a progenitor system, which contained a helium-star companion, the improvement of the BPS method may be required. Taking uncertainties on the BPS method into account, we conclude that the possibility of a He star donor for SN 2012Z cannot be excluded, but the expected probability is very low.

Additionally, as mentioned by McCully et al. (2014), the possibility that SN 2012Z-S1 is a single massive star that itself exploded cannot be ruled out yet. Fortunately, it may be possible to distinguish between the Ch-mass binary model and the single massive-star model through *HST* imaging when SN 2012Z will have faded below the brightness of SN 2012Z-S1 (see also McCully et al. 2014). The simulations for weak deflagration explosions of the Ch-mass WD (Jordan et al. 2012; Kromer et al. 2013, 2015; Fink et al. 2014) showed that an abundance-enriched bound remnant of the WD will be left after the SN explosion. Also, the companion stars (Marietta et al. 2000; Liu et al. 2012, 2013a, 2013b, 2013c; Pan et al. 2013) are expected to survive from the SN explosion. If the SN 2012Z produces from the C/O WD (or hybrid C/O/Ne WD)+He star scenario, a surviving bound remnant of the WD and He companion star would probably be detected in the SN remnants though some distinct features during their long-term post-explosion evolution such as a spatial velocity (if the binary system can be destroyed by the SN explosion, see Jordan et al. 2012), a particular luminosity evolution (Pan et al. 2013; Foley et al. 2014) or even a heavy-element enrichment (Liu et al. 2013c; Pan et al. 2013).

4.3. Uncertainties

In the SD scenario, only a fairly narrow range in the accretion rate will allow stable H- or He-burning to be attained on the surface of the WD, avoiding a nova explosion. In this work, the prescription of optically thick wind model from Hachisu et al. (1999) and He-retention efficiencies from Kato & Hachisu (2004) are used to describe the mass accumulation efficiency of accreting WDs. However, strong constraints on the uncertainties of the mass-retention efficiencies are still lacking (e.g., Shen & Bildsten 2007; Wolf et al. 2013; Piersanti et al. 2014). Different mass-retention efficiencies are expected to somewhat change the results from our binary calculations and thus the BPS results (e.g., see Bours et al. 2013; Piersanti et al. 2014; Ruiter et al. 2014; Toonen et al. 2014). However, we do not expect a significant change in the main conclusions presented in this paper. This issue will be addressed in detail in a forthcoming study.

In addition, there is a selection effect due to the initial conditions ($M^i_{\rm WD}$, M^i_2, $\log_{10} P^i$) of the populations. The initial conditions of BPS calculations may sensitively rely on the assumed parameters in specific BPS code, which will lead to some uncertainties on the BPS results (Toonen et al. 2014). For instance, CE evolution, current SFR and initial mass function. However, current constraints on these parameters (e.g., the CE efficiency, see Zorotovic et al. 2010; De Marco et al. 2011; Ivanova et al. 2013) are still weak. For a detailed discussion for the effect of different theoretical uncertainties, see Claeys et al. (2014).

5. CONCLUSION AND SUMMARY

Some potential progenitor scenarios have been proposed to explain the observational properties of SNe Iax. Although weak deflagrations of Ch-mass WDs seem to be the most promising scenario for SNe Iax (Jordan et al. 2012; Foley et al. 2013; Kromer et al. 2013; Fink et al. 2014; McCully et al. 2014), including the faint SNe Iax such as 2008ha-like events (Kromer et al. 2015). However, the nature of the progenitor systems of SNe Iax is still unclear. In this work, we predict observational features of companion stars of binary progenitor systems at the moment of the SN Iax explosion by performing detailed binary evolution calculations with the 1D stellar evolution code STARS, which will be very helpful for constraining the progenitor systems of SNe Iax through their pre-explosion imaging (e.g., McCully et al. 2014; Foley et al. 2015).

Comparing our results with the observations of SN 2012Z-S1, it is found that our detailed binary evolution calculations for the C/O WD+He star and hybrid WD+He star Ch-mass channel can contribute significantly to the number of systems in the vicinity of SN 2012Z-S1, but it seems the hybrid WD+He star Ch-mass channel is more favorable for the observations of SN 2012Z-S1. However, our BPS calculations for both the C/O WD+He star and the hybrid WD+He star Ch-mass channel produces companion stars as cool as the SN 2012Z-S1 only at very low probability. We thus conclude that the possibility of the He donor star as a companion of SN 2012Z is low based on our BPS predictions, but the possibility cannot be excluded. A further confirmation needs future observations after SN 2012Z will have faded below the brightness of SN 2012Z-S1.

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