COMPANION STARS OF TYPE Ia SUPERNOVAE

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ABSTRACT

The WD+MS channel of the single-degenerate scenario is currently favorable for progenitors of Type Ia supernovae (SNe Ia). Incorporating the results of detailed binary evolution calculations for this channel into the latest version of a binary population synthesis code, I obtained the distributions of many properties of the companion stars at the moment of SN explosion. The properties can be verified by future observations.

Subject headings: binaries: close — stars: evolution — supernovae: general — white dwarfs

Online material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) have been used as a calibrated candle to probe the dynamics of the universe, leading to a significant progress in cosmology, i.e., the determination of $\Lambda$ and $\Omega$ (Riess et al. 1998; Perlmutter et al. 1999). They are believed to be thermonuclear explosions of carbon-oxygen (CO) white dwarfs (WDs). However, the nature of their progenitors has remained unclear, and this still raises doubts as to the calibration which is purely empirical and based on the nearby SN Ia sample. Based on the characteristics of observed SNe Ia (e.g., light curves, chemical stratification), it seems most likely that they occur when the accreting CO WDs reach the Chandrasekhar limit, and sub-Chandrasekhar models appear not to be consistent with the observations of SNe Ia. Chandrasekhar-mass WDs can be created through the single-degenerate scenario, where the CO WD accretes mass from a nondegenerate companion (Nomoto et al. 1984; Hachisu et al. 1999), or the double-degenerate scenario, where two CO WDs with a total mass larger than the Chandrasekhar mass coalesce (Iben & Tutukov 1984; Webbink & Iben 1987).1 Recent observations indicate that there is a wide spread of delay time between star formation and SN Ia explosion, and this implies that there exist two populations of progenitors, a “prompt” one with a delay time of less than ~0.1 Gyr, and a “tardy” one with a delay time of ~3 Gyr (Mannucci et al. 2006).

Using the archival data prior to explosion from the Hubble Space Telescope (HST) and Chandra, Voss & Nelemans (2008) tried to search for a possible progenitor of SN 2007on (Type Ia) in elliptical galaxy NGC 1404. They discovered an object at the position of SN 2007on. The X-ray luminosity of the object and the nondetection in the optical images are fully consistent with the single-degenerate scenario, and the discovery therefore favors the single-degenerate scenario. However, new Chandra X-ray observations (Roelofs et al. 2008) and detailed astrometry of the site of SN 2007on showed that there appears to be an offset between the SN and the X-ray source, and the offset means a small probability (~1%) of the X-ray source being related to the SN. However, the X-ray source is not unconnected with the SN, as the X-ray source has dimmed after the explosion and the source before the explosion showed an excess of soft X-ray photons relative to the other sources in the field. Kepler’s 1604 supernova is suggested to be of Type Ia. Reynolds et al. (2007) made a deep Chandra observation of Kepler’s supernova remnant and concluded that Kepler’s SN is an SN Ia with circumstellar medium (CSM) interaction. This might indicate that the progenitor is a massive (young) star. Maoz & Mannucci (2008) searched HST preexplosion images for NGC 1316, a radio galaxy in the Fornax Cluster and a prolific producer of SNe Ia, for evolved intermediate-mass progenitor stars. The preexplosion images (3 years before explosion) of the sites of SN 2006dd (a normal SN Ia) and SN 2006mr (likely a subluminous SN Ia) show no potential luminous stellar progenitors. More effort is still needed in identifying the progenitors of SNe Ia.

Among various possible progenitor models, the WD+MS channel of the single-degenerate scenario is the most widely accepted one, in which a CO WD accretes mass from its main-sequence (MS) star or a slightly evolved subgiant in a close binary system until it reaches a mass of ~1.378 $M_\odot$, and explodes as an SN Ia (Nomoto et al. 1984; Li & van den Heuvel 1997; Hachisu et al. 1999; Langer et al. 2000; Han & Podsiadlowski 2004). The companion star should survive the explosion and show distinguishing properties, and it is therefore a promising method to test progenitor models by identifying the surviving companion stars of SNe Ia.

Tycho Brahe’s 1572 supernova is a Galactic SN Ia. Ruiz-Lapuente et al. (2004) found in the remnant region that Tycho G, a star similar to the Sun but with a lower gravity, moves at more than 3 times the mean velocity of the stars there. They argued that Tycho G could be the surviving companion of the supernova.2 Indeed, a surviving companion would have a high space velocity and evolve to a WD finally, and the single-degenerate scenario could potentially explain the properties of halo WDs observed by Oppenheimer et al. (2001), e.g., their space density and ages (Hansen 2003; Bergeron 2003). Furthermore, Justham et al. (2008) argued that the ultracool WDs observed by Wolf (2005) might have been formed via the single-degenerate scenario; i.e., they might be the remnants of the nondegenerate donor stars. Note, however, there has been no conclusive proof yet that any individual object is the surviving companion of an SN Ia.

Langer et al. (2000) did detailed binary evolution calculations for part of the WD+MS channel of the single-degenerate scenario, and presented the properties, e.g., orbital velocities, luminosities, and effective temperatures, of the companion stars at the moment of SN Ia explosion for the sample WD binaries they studied, in which the Roche lobe overflow (RLOF) starts when the companion star is in MS. However, the distributions

1 Note, it is quite likely that the merger product experiences core collapse rather than a thermonuclear explosion.

2 However, Fuhrmann (2005) argued that there exists a possibility of Tycho G being a thick-disk star coincidentally passing in the vicinity of the remnant of SN 1572.
of the properties have not been obtained. Canal et al. (2001) run a Monte Carlo scenario code to calculate the distributions of masses, luminosities, and velocities of the companion stars of SNe Ia. However, they have not done detailed binary evolution calculations for the production of SNe Ia, and this results in large uncertainties (see Han & Podsiadlowski 2004); e.g., the orbital velocities obtained for the companion stars from the WD+MS channel are over 450 km s$^{-1}$, which is far too high.

Han & Podsiadlowski (2004, hereafter HP04) carried out detailed binary evolution calculations for the WD+MS channel for about 2300 close WD binaries, in which RLOF starts when the companion star is in the MS or Hertzsprung gap (i.e., slightly evolved). The study is comprehensive, and various properties of the companion stars were obtained but not sorted for publishing. In this Letter, I extract the properties from the data files of the calculations and incorporate them into the latest version of the binary population synthesis (BPS) code developed for the study of various binary-related objects (Han et al. 1995a, 1995b, 2002, 2003; Han 1998), including the progenitors of SNe Ia (Han & Podsiadlowski 2004, 2006), and obtain the distributions of the properties.

2. THE DISTRIBUTIONS OF PROPERTIES OF THE COMPANION STARS

In the single-degenerate scenario, the progenitor of an SN Ia is a close WD binary system, which has most likely emerged from common envelope (CE) evolution (Paczynski 1976) of a giant binary system. During the CE evolution, the envelope engulfs the core (here a CO WD) of the giant and the secondary, and the orbital energy released in the spiral-in process (i.e., orbital decay) is used to overcome the binding energy of the CE in order to eject it. For the CE evolution, I have two parameters: $\alpha_{\text{CE}}$, the CE ejection efficiency, i.e., the fraction of the released orbital energy used to overcome the binding energy, and $\alpha_{\text{th}}$, which defines the fraction of the thermal energy contributing to the binding energy of the CE. As in previous studies, I adopted $\alpha_{\text{CE}} = \alpha_{\text{th}} = 1.0$, which gives good matches between theory and observations for many binary-related objects.$^3$

$^3$ The prescription adopted here for the CE evolution is different from the $\lambda$ prescription, but appears to be more physical. See Han et al. (1995b), Dewi & Tauris (2000), and Podsiadlowski et al. (2003) for details.
To obtain the distributions of properties of companion stars at the moment of SN explosion, I have performed a detailed Monte Carlo simulation with the latest version of the BPS code. The code follows the evolution of binaries with their properties being recorded at every step. If a binary system evolves to a WD+MS system, and if the system, at the beginning of the RLOF phase, is located in the SN Ia production regions in the plane of \((\log P^*, M^2)\) for its \(M^w_\text{WD}^i\), where \(P^*, M^i_\text{WD}\), and \(M^w_\text{WD}\) are, respectively, the orbital period, the secondary’s mass, and the WD’s mass of the WD+MS system at the beginning of the RLOF (see Fig. 3 of HP04), I 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 \((M^w_\text{WD}, M^i_\text{WD}; \log P^*)\) of the \(\sim 2300\) close WD binaries calculated in HP04.

In the simulation, I follow the evolution of 100 million sample binaries according to grids of stellar models of metallicity \(Z = 0.02\) and the evolution channels leading to SNe Ia as described in HP04. I adopted the following input for the simulation (see Han et al. 1995b). (1) The star formation rate (SFR) is taken to be constant over the last 15 Gyr. (2) The initial mass function (IMF) of Miller & Scalo (1979) is adopted. (3) The mass-ratio distribution is taken to be constant. (4) The distribution of separations is taken to be constant in \(\log a\) for wide binaries, where \(a\) is the orbital separation. (5) The orbits are assumed to be circular.

The simulation gives current-epoch-snapshot distributions of many properties of companion stars at the moment of SN explosion, e.g., the masses, the orbital periods, the orbital separations, the orbital velocities, the effective temperatures, the luminosities, the surface gravities, the surface abundances, the mass transfer rates, and the mass-loss rates of the optically thick stellar winds. The simulation also shows the initial parameters of the primordial binaries and the WD binaries that lead to SNe Ia. Figures 1–7 are selected distributions that may be helpful to identify the progenitors of SNe Ia.

### 3. DISCUSSION

Figures 1 and 2 are the distributions of the masses, the orbital velocities, the effective temperatures, and the surface gravities of companion stars at the moment of SN explosion. Tycho G was taken as the surviving companion star of Tycho Brahe’s 1572 supernova by Ruiz-Lapuente et al. (2004). It has a space velocity of 136 km s\(^{-1}\), more than 3 times the mean velocity there. Its surface gravity is \(\log (g/cm s^{-2}) = 3.5 \pm 0.5\), while the effective temperature is \(T_{\text{eff}} = 5750 \pm 250\) K. The parameters are compatible with Figures 1 and 2. As from our simulation, the recorded properties at each step show that a primordial binary system with a primary mass \(M_1 \sim 4–5.5 M_\odot\), a secondary mass \(M_2 \sim 2–3 M_\odot\), and an orbital period \(P \sim 100–250\) days would evolve to a close WD binary system with a WD mass \(M_{\text{WD}}^i \sim 0.8–1.2 M_\odot\), a secondary mass \(M^i_\text{WD}^f \sim 2–3 M_\odot\), and an orbital period \(P^f \sim 1–4\) days. The WD binary results in SN Ia explosion with companion parameters \((T_{\text{eff}}\) and \(\log g\) actually) in the range of Tycho G.

However, Figures 1 and 2 are for the moment of SN explosion; the distributions could be modified due to the explosion. Marietta et al. (2000) presented several high-resolution two-dimensional numerical simulations of the impacts of SN Ia explosion with companions. The impact makes the companion in the WD+MS channel lose a mass of \(0.15–0.17 M_\odot\) and receive a kick of \(49–86\) km s\(^{-1}\). Meng et al. (2007) adopted the simple analytic method of Wheeler et al. (1975) and calculated the impact to survey the influence of the initial parameters of the progenitor’s systems. With detailed stellar models and realistic separations that were obtained

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4 The Chandrasekhar-mass WD has an orbital velocity of \(\sim 50 \text{ to } 200\) km s\(^{-1}\) for a corresponding companion star’s mass of \(\sim 0.6 \text{ to } 2.0 M_\odot\) at the moment of SN explosion.
from binary evolution, they obtained an even lower “stripped mass,” 0.03-0.13 $M_\odot$, but a similar kick velocity 30-90 km s$^{-1}$, which is perpendicular to the orbital velocity. A surviving companion star therefore has a mass lower by $\sim0.1 M_\odot$ and a space velocity larger by $\sim10\%$ than that in Figure 1.

The companion stars are out of thermal equilibrium at the moment of SN explosion. The equilibrium radii are typically larger by $\sim50\%$ than that at the moment of SN explosion. Therefore the surface gravity at equilibrium should be lower than that in Figure 2. Podsiadlowski (2003) systematically explored the evolution and appearance of a typical companion star that has been stripped and heated by the supernova interaction during the postimpact re-equilibrium phase. Such a star may be significantly overluminous or underluminous. Figure 2 could be a starting point for further studies of this kind.

Figure 3 is the distribution of orbital periods of the WD+MS systems at the moment of SN explosion. If I assume that the companion stars corotate with their orbits, I obtain their distributions of equatorial rotational velocities (see Fig. 4). We see that the surviving companion stars are fast rotators and their spectral lines should be broadened noticeably.

Figure 5 shows the distribution of masses lost during optically thick stellar wind phase. We see that a significant amount of mass is lost in the wind. Badenes et al. (2007) found that the wind with a velocity above 200 km s$^{-1}$, which is believed to be reasonable, would excavate a large low-density cavity around its progenitor. However, the fundamental properties of seven young SN Ia remnants (Kepler, Tycho, SN 1006, 0509-67.5, 0519-69.0, N103B, and SN 1885) obtained by Badenes et al. (2007) are incompatible with such large cavities. A lower wind velocity or the consideration of WD rotation could help to solve the problem (Badenes et al. 2007).

Figure 6 presents the distribution of mass transfer rates at the moment of SN explosion. The mass transfer rates can be converted to X-ray luminosities of the systems by $L_X \sim \epsilon [M]$, where $\epsilon = 7 \times 10^{37}$ erg s$^{-1}$ gives the approximate amount of energy obtained per gram of hydrogen burnt into helium or carbon/oxygen. The luminosity of the X-ray source close to the site of SN 2007on (4 years before the explosion) was estimated to be $(3.3 \pm 1.5) \times 10^{37}$ erg s$^{-1}$ (Voss & Nelemans 2008), corresponding to a mass accretion rate of $\sim10^{-7} M_\odot$ yr$^{-1}$, which is consistent with Figure 6.

QU Carinae, a cataclysmic variable (CV), is suspected of being an SN Ia progenitor. It has a WD mass of $\sim1.2 M_\odot$, a once-reported orbital period of 0.45 days, and more importantly, a very high mass transfer rate of $\sim10^{-7} M_\odot$ yr$^{-1}$ (Kafka et al. 2008). These properties are consistent with Figures 3 and 6. However, BF Eridani, another CV with $M_{WD} \sim 1.28 M_\odot$, $M_\star \sim 0.52 M_\odot$, and $P \sim 0.27$ days (Neustroev & Zharkov 2008), appears not to be an SN Ia progenitor.

Figure 7 is the distribution of the surface nitrogen mass fraction of companion stars at the moment of explosion. We see that nitrogen can be significantly overabundant (with corresponding underabundance of carbon due to the CN cycle). However, the surface can be seriously polluted by the ejecta of SN explosions.

The simulation in this Letter was made with $\alpha_{CV} = \alpha_{in} = 1.0$. If I adopt a lower value for $\alpha_{CV}$, say, 0.1, the birth rate of SNe Ia would be higher (a factor of 1.7) and the delay time from the star formation to SN explosion is shorter. This is because binaries resulting from CE ejections tend to have shorter orbital periods for a small $\alpha_{CV}$ and are more likely to locate in the SN Ia production region (see Fig. 3 of HP04). The companion stars with orbital velocity $V < 110$ km s$^{-1}$ would be absent from Figure 1, and the ones with log ($g/cm^2$) $< 3.1$ would be absent from Figure 2. This is due to WD binaries with long orbital periods being absent because of a small $\alpha_{CV}$.

The distributions are snapshots at current epoch for a constant SFR. For a single starburst, most of the SN explosions occur between 0.1 and 1 Gyr after the burst (see Fig. 7 of HP04). The evolution of progenitor properties with time can be understood via Figure 3 of HP04. A delay time from 0.1 to 1 Gyr corresponds to $M_i$ of $\sim3.2$ to $\sim1.8 M_\odot$, and to $M_{WD}$ of $\sim1.2$ to $\sim0.67 M_\odot$ for the WD+MS system, respectively. As seen from Figure 3 of HP04, the range of the orbital periods becomes narrower from a delay time of 0.1 to 1.0 Gyr. Those WD binaries result in SN Ia explosions via RLOF. Consequently, the range of progenitor properties at the moment of SN Ia, e.g., the orbital velocities of companion stars, the surface gravities, the equatorial rotational velocities, and the mass transfer rates, becomes narrower with time. The mass transfer rate would be smaller with time as $M_i$ becomes smaller.

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