WD + He star systems as the progenitors of Type Ia supernovae and their surviving companion stars

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Abstract Employing Eggleton’s stellar evolution code with an optically thick wind assumption, we have systematically studied the WD + He star channel of Type Ia supernovae (SNe Ia), in which a carbon-oxygen WD accretes material from a He main-sequence star or a He subgiant to increase its mass to the Chandrasekhar mass. We mapped out the parameter spaces for producing SNe Ia. According to a detailed binary population synthesis approach, we find that the Galactic SN Ia birthrate from this channel is \( \sim 0.3 \times 10^{-3} \, \text{yr}^{-1} \), and that this channel can produce SNe Ia with short delay times (\( \sim 45–140 \, \text{Myr} \)). We also find that the surviving companion stars in this channel have a high spatial velocity (\( > 400 \, \text{km/s} \)) after SN explosion, which could be an alternative origin for hypervelocity stars (HVSs), especially for HVSs such as US 708.

Keywords binaries: close · stars: evolution · supernovae: general · white dwarfs

1 Introduction

Type Ia supernovae (SNe Ia) play an important role in the study of cosmic evolution, especially in cosmology. They have been applied successfully in determining cosmological parameters (e.g. \( \Omega \) and \( \Lambda \); Riess et al. 1998; Perlmutter et al. 1999). It is generally believed that SNe Ia are thermonuclear explosions of carbon-oxygen white dwarfs (CO WDs) in binaries. However, there is still no agreement on the nature of their progenitors (Hillebrandt and Niemeyer 2000; Podsiadlowski et al. 2008; Wang et al. 2008).

Over the past few decades, two families of SN Ia progenitor models have been proposed, i.e. the double-degenerate (DD) and single-degenerate (SD) models. Of these two models, the SD model is widely accepted at present. It is suggested that the DD model, which involves the merger of two CO WDs (Iben & Tutukov 1984; Webbink 1984; Han 1998), likely leads to an accretion-induced collapse rather than to an SN Ia (Nomoto and Iben 1985). For the SD model, the companion is probably a main-sequence (MS) star or a slightly evolved subgiant star (WD + MS channel), or a red-giant star (WD + RG channel) (Hachisu et al. 1996; Li and van den Heuvel 1997; Langer et al. 2000; Han and Podsadlowski 2004, 2006; Chen and Li 2007, 2009; Lü et al. 2009; Meng et al. 2009; Wang, Li and Han 2009; Meng and Yang 2009a). Meanwhile, a CO WD may also accrete material from a He star to increase its mass to the Chandrasekhar (Ch) mass, which is known as the WD + He star channel. Yoon and Langer (2003) followed the evolution of a CO WD + He star system, in which the WD can increase its mass to the Ch mass by accreting material from the He star. It is believed that WD + He star systems are generally originated from intermediate mass binaries, which may explain SNe Ia with short delay times implied by recent observations (Mannucci et al. 2006, Aubourg et al. 2008).

The purpose of this paper is to study SN Ia birthrates and delay times of the WD + He star channel and to explore the properties of the surviving companion stars after SN explosion. In Section 2, we describe the numerical code for the binary evolution calculations and the binary evolutionary results. We describe the binary population synthesis (BPS) method and results in Section 3. Finally, a discussion is given in Section 4.
Fig. 1 Regions in orbital period–secondary mass plane for WD binaries that produce SNe Ia for initial WD masses of 0.9, 1.0, 1.1 and 1.2 $M_\odot$. The lowest WD mass for producing SNe Ia in this channel is 0.865 $M_\odot$.

2 Binary evolution calculations

We use Eggleton’s stellar evolution code (Eggleton 1971, 1972, 1973) to calculate the binary evolutions of WD + He star systems. The code has been updated with the latest input physics over the past three decades (Han et al. 1994; Pols et al. 1995, 1998). Roche lobe overflow (RLOF) is treated within the code described by Han et al. (2000). We set the ratio of mixing length to local pressure scale height, $\alpha = l/H_p$, to be 2.0. The opacity tables are compiled by Chen and Tout (2007). In our calculations, He star models are composed by He abundance $Y = 0.98$ and metallicity $Z = 0.02$.

Instead of solving stellar structure equations of a WD, we use an optically thick wind model (Hachisu et al. 1996) and adopt the prescription of Kato and Hachisu (2004) for the mass accumulation efficiency of He-shell flashes onto the WD. We have calculated about 2600 WD + He star systems, and obtain a large, dense model grid (for details see Wang et al. 2009a). In Fig. 1, we show the contours for producing SNe Ia. If the parameters of a WD binary at the onset of the RLOF are located in the contours, an SN Ia is then assumed to be produced. Thus, these contours can be expediently used in BPS studies.

3 Binary population synthesis

To obtain SN Ia birthrates and delay times of the WD + He star channel, we performed a series of Monte Carlo simulations in the BPS study. In the simulation, by using the Hurley’s rapid binary evolution code (Hurley et al. 2000, 2002), we followed the evolution of $4 \times 10^7$ sample binaries from the star formation to the formation of the WD + He star systems according to the SN Ia production regions (Fig. 1) and three evolutionary channels (i.e. the He star channel, the EAGB channel, and the TPAGB channel; for details see Wang et al. 2009b). Here, we adopt the standard energy equations to calculate the output of the common envelop (CE) phase (e.g. Wang et al. 2009b).

In the BPS study, the primordial binary samples are generated in the Monte Carlo way and a circular orbit is assumed for all binaries. We adopt the following input for the simulation (e.g. Han et al. 2002, 2003, 2007; Wang et al. 2009b). (1) The initial mass function (IMF) of Miller and Scalo (1979) is adopted. (2) The mass-ratio distribution is taken to be constant. (3) The distribution of separations is taken to be constant in $\log a$ for wide binaries, where $a$ is the orbital separation. (4) We simply assume a constant star formation rate (SFR) over the past 15 Gyr or, alternatively, as a delta function, i.e. a single starburst.

In Fig. 2, we show Galactic birthrates of SNe Ia for the WD + He star channel by adopting $Z = 0.02$
The simulations give Galactic SN Ia birthrate of \( \sim 0.3 \times 10^{-3} \text{ yr}^{-1} \). Figure 3 displays the evolution of SN Ia birthrates for a single starburst with a total mass of \( 10^{11} M_\odot \). In the figure, we see that SN Ia explosions occur between \( \sim 45 \) Myr and \( \sim 140 \) Myr after the starburst, which may explain SNe Ia with short delay times.

The companion star in the SD model would survive in the SN explosion and potentially be identifiable (Podsiadlowski 2003; Han 2008; Meng and Yang 2009). We obtained the distributions of many properties of the companion stars of this channel at the moment of SN explosion (e.g. Wang and Han 2009). We can give the spatial velocity of the surviving companion stars, based on the formula 
\[
V_{\text{SN}}^2 = \frac{V_{\text{kick}}^2 + V_{\text{orb}}^2}{2},
\]
where \( V_{\text{kick}} \) and \( V_{\text{orb}} \) are the kick velocity and the orbital velocity of the companion star at the moment of SN explosion, respectively. The kick velocity depends on the ratio of separation to the radius of companions at the moment of SN explosion, \( A/R_2^{\text{SN}} \), and the leading head velocity of SN ejecta (Meng et al. 2007). Here, the leading head velocity is assumed to be \( 13500 \text{ km/s} \), which is from the SN ejecta kinetic energy \( 1.5 \times 10^{51} \text{ erg} \) corresponding to the upper limit of the kinetic energy of normal SNe Ia (Gamezo et al. 2003). In Fig. 4, we show the current epoch distribution of the spatial velocity for the surviving companions from this channel. We see that the surviving companion stars have high spatial velocities (\( > 400 \text{ km/s} \)), which almost exceed the gravitational pull of the Galaxy nearby the sun. Thus, the surviving companion stars from the WD + He star channel could be an alternative origin for hypervelocity stars (HVSs), which are stars with a velocity so great that they are able to escape the gravitational pull of the Galaxy.

4 Discussion

The simulations give Galactic SN Ia birthrate of \( \sim 0.3 \times 10^{-3} \text{ yr}^{-1} \), which is lower than that inferred observationally (i.e. \( 3 - 4 \times 10^{-3} \text{ yr}^{-1} \); Cappellaro and Turatto 1997). This implies that the WD + He star channel is only a subclass of SN Ia production, and there may be some other channels or mechanisms also contributing to SNe Ia, e.g. WD + MS channel, WD + RG channel or double-degenerate channel (see Wang, Li and Han 2009; Meng and Yang 2009).

In this paper, we assume that all stars are in binaries and about 50% of stellar systems have orbital periods less than 100 yr. If we adopt 46.3% of stellar systems have orbital periods below 100 yr by adjusting the parameter \( a_1 \) in equation (7) of Wang et al. (2009b), the SN Ia birthrate from this channel will decrease to be \( \sim 0.28 \times 10^{-3} \text{ yr}^{-1} \).

Hachisu et al. (2008) investigated new evolutionary models for SN Ia progenitors, introducing the mass-stripping effect on a MS or slightly evolved companion star by winds from a mass-accreting WD. The model can also provide a possible ways of producing young SNe Ia, but the model depends on the efficiency of the mass-stripping effect. We also find that the model produces very few young SNe Ia according to a detailed BPS approach. Thus, we consider the WD + He star channel as a main contribution to the formation of young SNe Ia.

US 708 is an extremely He-rich sdO star in the Galaxy halo, with a heliocentric radial velocity of \( \pm 708 \pm 15 \text{ km/s} \) (Hirsch et al. 2005). We note that the local velocity relative to the Galactic center may lead to a higher observation velocity for the surviving companion stars, but this may also lead to a lower observation velocity. Considering the local velocity near the sun (\( \sim 220 \text{ km/s} \)), we find that \( \sim 30\% \) of the surviving companion stars may be observed to have velocity \( V > 700 \text{ km/s} \). In addition, the asymmetric explosion of SNe Ia may also enhance the velocity of the surviving companions. Thus, a surviving companion star in the WD + He star channel may have a high velocity like US 708 (see also Justham et al. 2008).

For a single starburst, most of the SN explosions occur between \( \sim 45 \text{ Myr} \) and \( \sim 140 \text{ Myr} \) after the starburst, i.e. SNe Ia from the WD + He star channel will be absent in the old galaxies. In future investigations, we will employ the Large sky Area Multi-Object...
fiber Spectral Telescope (LAMOST) to search the HVSs originating from the surviving companions of SNe Ia.

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References

Aubourg, E., Tojeiro, R., Jimenez, R., Heavens, A.F., Strauss, M.A., Spergel, D.N.: Astron. Astrophys. 492, 631–636 (2008)
Cappellaro, E., Turatto, M.: in Thermanuclear Supernovae, ed. P. Ruiz-Lapuente, R. Cannal, J. Isen (Dordrecht: Kluwer), 77 (1997)
Chen, X., Tout, C.A.: Chin. J. Astro. Astrophys. 7, 245–250 (2007)
Chen, W.-C., Li, X.-D.: Astrophys. J. 658, L51–L54 (2007)
Chen, W.-C., Li, X.-D.: Astrophys. J. 702, 686–691 (2009)
Eggleton, P.P.: Mon. Not. Roy. Astron. Soc. 151, 351–364 (1971)
Eggleton, P.P.: Mon. Not. Roy. Astron. Soc. 156, 361–376 (1972)
Eggleton, P.P.: Mon. Not. Roy. Astron. Soc. 163, 279–284 (1973)
Gamezo, V.N., Khokhlov, A.M., Oran, E.S., Chctchellkanova, A.Y., Rosenberg, R.O.: Sci. 299, 77–81 (2003)
Hachisu, I., Kato, M., Nomoto, K.: Astrophys. J. 470, L97–L100 (1996)
Hachisu, I., Kato, M., Nomoto, K.: Astrophys. J. 679, 1390–1404 (2008)
Han, Z.: Mon. Not. Roy. Astron. Soc. 296, 1019–1040 (1998)
Han, Z.: Astrophys. J. 677, L109–L112 (2008)
Han, Z., Podsiadlowski, Ph.: Mon. Not. Roy. Astron. Soc. 350, 1301–1309 (2004)
Han, Z., Podsiadlowski, Ph.: Mon. Not. Roy. Astron. Soc. 368, 1095–1100 (2006)
Han, Z., Podsiadlowski, Ph., Eggleton, P.P.: Mon. Not. Roy. Astron. Soc. 270, 121–130 (1994)
Han, Z., Podsiadlowski, Ph., Lynas-Gray, A.E.: Mon. Not. Roy. Astron. Soc. 380, 1098–1118 (2007)
Han, Z., Podsiadlowski, Ph., Maxted, P.F.L., Marsh, T.R.: Mon. Not. Roy. Astron. Soc. 341, 669–691 (2003)
Han, Z., Podsiadlowski, Ph., Maxted, P.F.L., Marsh, T.R., Ivanova, N.: Mon. Not. Roy. Astron. Soc. 336, 449–466 (2002)
Han, Z., Tout, C.A., Eggleton, P.P.: Mon. Not. Roy. Astron. Soc. 319, 215–222 (2000)
Hillebrandt, W., Niemeyer, J.C.: ARA&A 38, 191–230 (2000)
Hirsch, H.A., Heber, U., O’Toole, S.J., Bresolin, F.: Astron. Astrophys. 444, L61–L64 (2005)
Hurley, J.R., Pols, O.R., Tout, C.A.: Mon. Not. Roy. Astron. Soc. 315, 543–569 (2000)
Hurley, J.R., Tout, C.A., Pols, O.R.: Mon. Not. Roy. Astron. Soc. 329, 897–928 (2002)
Iben, I., Tutukov, A.V.: Astrophys. J. 431, 264–272 (1994)
Justham, S., Wolf, C., Podsiadlowski, Ph., Han, Z.: Astron. Astrophys. 493, 1081–1091 (2009)
Kato, M., Hachisu, I.: Astrophys. J. 613, L129–L132 (2004)
Langer, N., Deutschmann, A., Wellstein, S., Höflich, P.: Astron. Astrophys. 362, 1046–1064 (2000)
Li, X.-D., van den Heuvel, E.P.J.: Astron. Astrophys. 322, L9–L12 (1997)
Lü, G., Zhu, C., Wang, Z., Wang, N.: Mon. Not. Roy. Astron. Soc. 396, 1086–1095 (2009)
Mannucci, F., Della Valle, M., Panagia, N.: Mon. Not. Roy. Astron. Soc. 370, 773–783 (2006)
Meng, X., Chen, X., Han, Z.: PASJ. 59, 835–840 (2007)
Meng, X., Chen, X., Han, Z.: Mon. Not. Roy. Astron. Soc. 395, 2103–2116 (2009)
Meng, X., Yang, W.: submitted to Astrophys. J. (arXiv:0910.4902) (2009a)
Meng, X., Yang, W.: Mon. Not. Roy. Astron. Soc. in press (arXiv:0910.2167) (2009b)
Miller, G.E., Scalo, J.M.: Astrophys. J. Sup. Ser. 41, 513–547 (1979)
Nomoto, K., Iben, I.: Astrophys. J. 297, 531–537 (1985)
Perlmutter, S., et al.: Astrophys. J. 517, 565–586 (1999)
Podsiadlowski, Ph., Mazzali, P., Lesaffre, P., Han, Z., Förster, F.: New Astro. Rev. 52, 381–385 (2008)
Podsiadlowski, Ph.: preprint (astro-ph/0303660) (2003)
Pols, O.R., Schröder, K.P., Hurly, J.R., Tout, C.A., Eggleton, P.P.: Mon. Not. Roy. Astron. Soc. 298, 525–536 (1998)
Pols, O.R., Tout, C.A., Eggleton, P.P., Han, Z.: Mon. Not. Roy. Astron. Soc. 274, 964–974 (1995)
Riess, A., et al.: Astron. J. 116, 1009–1038 (1998)
Wang, B., Han, Z.: Astron. Astrophys. in press (arXiv:0911.3316) (2009)
Wang, B., Li, X.-D., Han, Z.: Mon. Not. Roy. Astron. Soc. in press (doi:10.1111/j.1365-2966.2009.15857.x) (arXiv:0910.2138) (2009)
Wang, B., Meng, X., Wang, X., Han, Z.: Chin. J. Astro. Astrophysics. 8, 71–80 (2008)
Wang, B., Meng, X., Chen, X., Han, Z.: Mon. Not. Roy. Astron. Soc. 395, 847–854 (2009a)
Wang, B., Chen, X., Meng, X., Han, Z.: Astrophys. J. 701, 1540–1547 (2009b)
Webbink, R.F.: Astrophys. J. 277, 355–360 (1984)
Yoon, S.-C., Langer, N.: Astron. Astrophys. 412, L53–L56 (2003)

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