

Is the X-ray pulsating companion of HD 49798 a possible type Ia supernova progenitor?

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Abstract HD 49798 (a hydrogen depleted subdwarf O6 star) with its massive white dwarf (WD) companion has been suggested to be a progenitor candidate of a type Ia supernova (SN Ia). However, it is still uncertain whether the companion of HD 49798 is a carbon-oxygen (CO) WD or an oxygen-neon (ONe) WD. A CO WD will explode as an SN Ia when its mass grows and approaches the Chandrasekhar limit, but the outcome of an accreting ONe WD is likely to be a neutron star. We generated a series of Monte Carlo calculations that incorporate binary population synthesis to simulate the formation of ONe WD + He star systems. We found that there is almost no orbital period as large as HD 49798 with its WD companion in these ONe WD + He star systems based on our simulations, which means that the companion of HD 49798 might not be an ONe WD. We suggest that the companion of HD 49798 is most likely a CO WD, which can be expected to increase its mass to the Chandrasekhar limit by accreting He-rich material from HD 49798. Thus, HD 49798 and its companion may produce an SN Ia as a result of its future evolution.

Key words: binaries: close — stars: individual — stars: evolution — supernovae: general — white dwarfs

1 INTRODUCTION

Type Ia supernova (SN Ia) explosions are among the most luminous phenomena in the Universe, and play an important role in astrophysics. Due to the remarkable uniformity of their high luminosities, SNe Ia have been successfully used as standard cosmological distance indicators. It has been verified that the Universe is expanding at an increasing rate through the observation of SNe Ia, which reveals the existence of dark energy (e.g., Riess et al. 1998; Perlmutter et al. 1999). Furthermore, SN Ia explosions are also relatively important for galactic chemical evolution for the reason that a great amount of iron can be produced during this process (e.g., Greggio & Renzini 1983; Matteucci & Greggio 1986), and they are also accelerators of cosmic rays (e.g., Fang & Zhang 2012). However,

SN Ia progenitors and their explosion mechanisms are still uncertain, which may influence the accuracy of distance calculations that use them as indicators (e.g., Podsiadlowski et al. 2008; Howell 2011; Liu et al. 2012; Wang & Han 2012; Wang et al. 2013; Hillebrandt et al. 2013; Maoz et al. 2014).

A theoretical consensus has been reached that SNe Ia originate from thermonuclear runaway explosions of carbon-oxygen white dwarfs (CO WDs) in binaries (see Hoyle & Fowler 1960; Nomoto et al. 1997). When a CO WD increases its mass to approach the Chandrasekhar limit in a close binary, an SN Ia would be produced. However, a key issue is the uncertainty associated with the companion star. There are two competing progenitor models which are widely accepted, i.e., the single-degenerate model and the double-degenerate model. In the single-degenerate model, a CO WD accretes material from a non-degenerate companion so that its mass is increased. The companion in this model could be a main sequence (MS) star, a subgiant star, a red giant (RG) star or a helium (He) star (e.g., Whelan & Iben 1973; Nomoto et al. 1984; Li & van den Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004; Han & Podsiadlowski 2006; Meng et al. 2009; Xu & Li 2009; Wang et al. 2009a, 2010; Ablimit et al. 2014; Chen et al. 2014a; Geier et al. 2015). In the double-degenerate model, the merger of two CO WDs produces an SN Ia; the merger is due to the loss of orbital angular momentum driven by gravitational wave radiation (e.g., Tutukov & Yungelson 1981; Iben & Tutukov 1984; Webbink 1984; Han 1998; Chen et al. 2012).

The CO WD + He star channel is an emerging variant of the single-degenerate model which can naturally account for the absence of hydrogen lines in most spectra of observed SNe Ia. Wang et al. (2009a) systematically studied the CO WD + He star channel and derived the parameters related to the spatial separation that produces SNe Ia. They found that SNe Ia from this channel may contribute to SNe Ia with short delay times. In the observations, a number of massive WD + He star binaries have been found, e.g., V445 Pup, HD 49798 with its companion, CD-30 11223, KPD 193+2752, etc. All of these binaries are possible candidates of SN Ia progenitors (e.g., Geier et al. 2007, 2013; Kato et al. 2008; Woudt et al. 2009; Wang & Han 2010; Mereghetti et al. 2011). Among these observed WD + He star systems, HD 49798 with its massive compact companion is one of the more well studied binaries composed of a bright subdwarf star whose hydrogen has been depleted (Jaschek & Jaschek 1963) and a fast X-ray pulsar source which is a massive WD with a short spin period (Israel et al. 1997).

HD 49798/RX J0648.0-4418 is a single spectroscopic binary which has been extensively investigated. Jaschek & Jaschek (1963) first classified HD 49798 as a subdwarf O6 star and obtained variations in its radial velocity. The period of this binary was suggested to be 1.548 day (see Thackeray 1970; Stickland & Lloyd 1994). A soft X-ray emission source was first found by the Einstein Observatory in the position of HD 49798 (see Simon et al. 1979). According to detailed data from the Roentgen Satellite, Israel et al. (1997) found that the X-ray source in HD 49798/RX J0648.0-4418 is very soft and has a high-energy excess, and that the X-ray source has a pulsation period of 13.2 s. Bisscheroux et al. (1997) argued that the companion is a WD rather than a neutron star based on its low X-ray luminosity (see also Hamann et al. 1981; Mereghetti et al. 2011). Bisscheroux et al. (1997) suggested that the X-ray emission of this binary is from the wind accretion process of the compact object, in which the accretion rate from the stellar wind of HD 49798 is $\sim 10^{-10} - 10^{-11} M_{\odot} \text{ yr}^{-1}$. They also speculated that HD 49798 is at the He-shell burning stage, which might explain its high luminosity. Recently, Mereghetti et al. (2009) observed the object with the Newton X-ray Multi-Mirror Mission satellite during an X-ray eclipse. They gave the parameters of this binary as: $R_{\text{He}} = 1.45 \pm 0.25 R_{\odot}$, $M_{\text{He}} = 1.50 \pm 0.05 M_{\odot}$ for HD 49798 and $M_{\text{WD}} = 1.28 \pm 0.05 M_{\odot}$ for the WD companion.

Wang & Han (2010) recently performed a detailed binary evolutionary calculation for HD 49798/RX J0648.0-4418. The temperature and luminosity of HD 49798 derived from their calculations were consistent with those of observations (see fig. 1 of Wang & Han 2010). Their work indicates that HD 49798 will fill its Roche lobe after $\sim 4 \times 10^4 \text{ yr}$, and the WD companion of

HD 49798 will increase its mass to the Chandrasekhar limit by accreting He-rich material. However, it is still unknown which kind of WD the companion of HD 49798 is. If the compact companion is a CO WD, it will grow to be an SN Ia when the carbon is ignited in the center (or off-center) of the WD (e.g., Nomoto 1982). If the companion of HD 49798 is an ONe WD, Ne and Mg in the WD will start to capture electrons when the WD grows to the Chandrasekhar limit. During the deflagration of O and Ne, too little energy could be released to give rise to an explosion of the whole WD (Miyaji et al. 1980). Driven by the subsequent electron capture, the outcome of the WD should be a neutron star with a fast spin but not an SN Ia (e.g., Canal et al. 1980; Nomoto & Kondo 1991).

The purpose of this article is to examine whether the companion of HD 49798 is an ONe WD or not via a binary population synthesis (BPS) method. The BPS numerical code and the input physics are described in Section 2. In Section 3, we present the results of our calculations. The discussion and conclusions are provided in Section 4.

2 METHODS

By using Hurley's rapid binary evolution code (Hurley et al. 2000, 2002), we performed a series of Monte Carlo simulations to study the formation of ONe WD + He star systems. In this work, an ONe WD is formed by the envelope loss of a thermally pulsing asymptotic giant branch (TPAGB) star with $M_{\text{up}} \leq M \leq M_{\text{ec}}$, while a CO WD is formed by the envelope loss of a TPAGB star with $M < M_{\text{up}}$ (see Hurley et al. 2000), where M , M_{up} and M_{ec} are the initial mass of the AGB star, the minimum mass needed to undergo non-degenerate C ignition and the minimum mass needed for an AGB star to avoid electron capture on Ne and Mg in its core, respectively (see table 1 of Pols et al. 1998). In each simulation, 1×10^7 primordial binary systems were included. The current parameters of HD 49798 and its WD companion have been provided by Mereghetti et al. (2009, 2011), that is, the masses of the He star and the WD are $1.50 \pm 0.05 M_{\odot}$ and $1.28 \pm 0.05 M_{\odot}$, respectively. The orbital period of this binary is 1.548 day (Thackeray 1970). Moreover, HD 49798 is a slightly evolved He star which has not filled its Roche lobe yet; the He star will fill its Roche lobe after about 4×10^4 yr (see Wang & Han 2010), which means that the masses and the orbital period of the system are similar to the parameters at the beginning of the formation of the WD + He star system. Thus, if the companion of HD 49798 is an ONe WD, the parameters of this binary are more likely to be located within the contours of ONe WD + He star systems determined by Monte Carlo BPS simulations.

According to the evolutionary phase when the primordial primary first fills its Roche lobe, there are four scenarios which can produce ONe WD + He star systems (see Fig. 1), as follows:

Scenario A: When the primordial primary is a subgiant or first giant branch (FGB) star, it fills its Roche lobe. At this stage, the Roche lobe overflow (RLOF) is stable. At the end of the RLOF, the primordial primary becomes an He star. Subsequently, the He star continues to evolve and will fill its Roche lobe again at the He RG stage. As a result, an ONe WD + MS system is produced after RLOF. Then the MS star continues to evolve and will fill its Roche lobe at the subgiant or He-core burning phase. A common envelope (CE) may be formed due to the dynamically unstable mass transfer. If the CE ejection happens, an ONe WD + He star system would be produced.

Scenario B: When the primordial primary first fills its Roche lobe at the early asymptotic giant branch (EAGB) stage, the mass transfer is dynamically unstable, leading to the formation of a CE. After the CE ejection, the primary becomes an He RG star and the orbital separation decays sharply. Then the primary fills its Roche lobe again. In this case, the RLOF is stable. After the He-shell is exhausted, an ONe WD + MS system is produced. The MS star continues to evolve and may fill its Roche lobe at the subgiant or FGB stage. A CE will be formed due to the dynamically unstable mass transfer. If the CE can be ejected, an ONe WD + He star will be produced.

Scenario C: The primordial primary first fills its Roche lobe at the TPAGB stage and a CE may be formed due to the dynamically unstable mass transfer. After the CE ejection, an ONe WD +

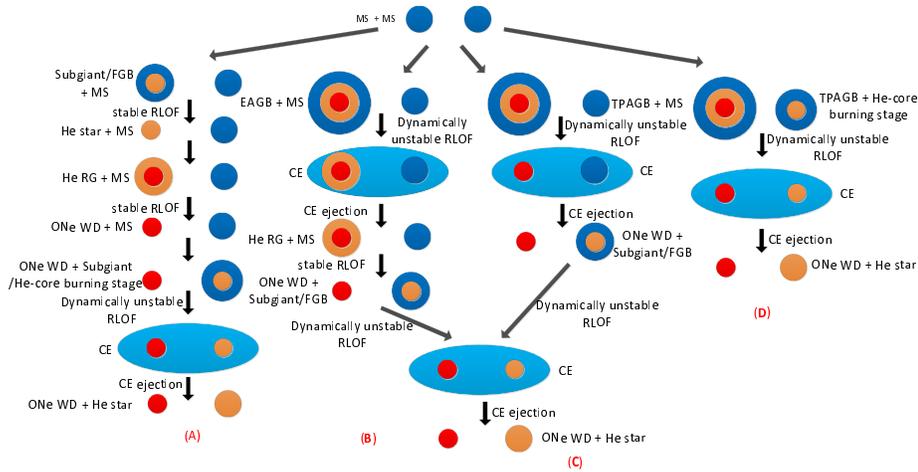


Fig. 1 Four binary evolutionary scenarios that produce ONe WD + He star systems.

Subgiant/FGB star system is formed. Subsequently, the binary evolution is similar to that of scenario B above and an ONe WD + He star system will be formed.

Scenario D: The primordial primary fills its Roche lobe when it is a TPAGB star and the primordial secondary is at the He-core burning phase. In this case, the mass transfer is dynamically unstable, leading to the formation of a CE. If the CE ejection happens, the primary becomes an ONe WD and the secondary becomes an He star, i.e., an ONe WD + He star system is produced.

Some basic assumptions in our BPS simulations are listed as follows:

- (1) The initial mass function described by Miller & Scalo (1979) is adopted. The primordial primary mass ranges from $0.1 M_{\odot}$ to $100 M_{\odot}$.
- (2) The primordial secondary mass is determined by the initial primordial primary mass and initial mass-ratio. For simplicity, a uniform mass-ratio distribution is adopted (e.g., Mazeh et al. 1992; Goldberg & Mazeh 1994).
- (3) The distribution of the separations of the initial orbit is constant in $\log(a)$ for wide binaries and falls off smoothly for close binaries (a is orbital separation), and all stars are set as members of binary systems with a circular orbit, and a boundary that separates close and wide binaries is set to be $10 R_{\odot}$ (Han et al. 1995).
- (4) The abundance of solar metallicity $Z = 0.02$ is adopted.
- (5) The process of RLOF is calculated by the method described in Tout et al. (1997).
- (6) The stable mass transfer process presented by Webbink (1985) is adopted.
- (7) The output of the CE stage is calculated by the standard energy equation (e.g., Webbink 1984), in which there are two uncertain parameters, i.e., the CE ejection efficiency (α_{CE}) and a stellar structure parameter (λ). Following the work of Wang et al. (2009b), we simply combine these two parameters into a single free parameter (i.e., $\lambda\alpha_{CE}$). In this work, we set $\lambda\alpha_{CE}$ to be 0.5, 1.0, 1.5 and 2.0 to examine its influence on the production of ONe WD + He star systems.¹

3 RESULTS

We conducted a series of Monte Carlo calculations incorporating a BPS approach to simulate the formation of ONe WD + He star systems. In Table 1, we present the initial parameters of the binaries

¹ Recent studies showed that the stellar structure parameter, λ , may be bigger during some particular stages (e.g., Xu & Li 2010; Zuo & Li 2014). Thus, we considered an extreme case with $\lambda\alpha_{CE} = 2.0$.

Table 1 Initial parameters of binaries which can evolve to ONe WD + He star systems. The simulation contains 1×10^7 primordial sample binaries, in which we set $\lambda_{\alpha_{\text{CE}}} = 1.0$.

Scenario	$M_{1,0}$ (M_{\odot})	$M_{2,0}$ (M_{\odot})	P_0 (d)	Number
(A)	8.0 – 11	2.5 – 10	2.0 – 960	2469
(B)	6.0 – 9.0	2.5 – 8.5	420 – 1600	1704
(C)	6.0 – 8.5	2.5 – 7.5	1400 – 6750	2027
(D)	6.0 – 8.5	6.0 – 8.5	1500 – 6000	227

Notes: $M_{1,0}$ = initial mass of the primordial primary; $M_{2,0}$ = initial mass of the primordial secondary; P_0 = initial orbital period of the primordial binary; Number = the number of ONe WD + He star systems produced from each scenario.

formed from those four scenarios which are shown in Figure 1 and give the number of ONe WD + He star systems produced from each scenario. From this table, we can see that these four scenarios are mainly distinguished by the difference in initial orbital periods, while the distinguishing factor between scenario C and scenario D is the initial mass ratio.

Based on the four cases of simulations with different CE ejection parameters (i.e., $\lambda_{\alpha_{\text{CE}}} = 0.5, 1.0, 1.5$ and 2.0), we obtained a total of about 28 000 ONe WD + He star binaries. From these binary systems, we selected binaries with an He star mass between 1.45 and $1.55 M_{\odot}$ which is consistent with the possible mass range of HD 49798.

Figure 2 shows the distribution of 937 ONe WD + He star systems in the initial orbital period and WD mass ($\log P^i - M_{\text{WD}}^i$) plane with the constraint defined by the mass of the He star. From this figure, we can see that as the value of $\lambda_{\alpha_{\text{CE}}}$ increases, the orbital separation tends to be wider and more ONe WD + He systems would be produced. This is because, for a larger value of $\lambda_{\alpha_{\text{CE}}}$, the ejection of CE will release less orbital energy and happen more easily. Note that the upper boundaries are determined by the existence of the Chandrasekhar limit for ONe WDs, while the lower boundaries are constrained by the minimum mass of WDs for the ignition of carbon to form ONe WDs. The ONe WD + He star systems beyond the left boundaries have their He star masses lower than the mass range of HD 49798, whereas they are larger than this mass range beyond the right boundary. Considering the cases with $\lambda_{\alpha_{\text{CE}}} = 0.5, 1.0$ and 1.5 , we can see that no ONe WD + He star system has a separation (orbital period) as large as HD 49798/RX J0648.0–4418 for the same masses of He stars, but for the extreme case with $\lambda_{\alpha_{\text{CE}}} = 2.0$, HD 49798/RX J0648.0–4418 is located on the boundary of the contour obtained for ONe WD + He star systems. However, the probability in this case is very low. We note that the extreme case with $\lambda_{\alpha_{\text{CE}}} = 2.0$ may not be physical in our simulations. Thus, we speculate that HD 49798 with its companion might not be an ONe WD + He star system.

In Figure 3, we present a more comprehensive distribution of orbital periods of ONe WD + He star systems without the constraints on the mass of the He star. From this figure, we can see that almost all the ONe WD + He star systems are distributed between 0.032 and 1.0 day. Regarding the orbital period of HD 49798/RX J0648.0–4418 (1.548 day), for the cases with $\lambda_{\alpha_{\text{CE}}} = 0.5, 1.0$ and 1.5 , it is still difficult to produce such a wide ONe WD + He star system even without the constraints of the He star mass; the orbital period of HD 49798/RX J0648.0–4418 can be reproduced by the extreme case with the value of $\lambda_{\alpha_{\text{CE}}} = 2.0$, but the probability is very low. Note that there are two peaks in the curves with $\lambda_{\alpha_{\text{CE}}} = 1.5$ and 2.0 , which are produced from different formation scenarios (see Fig. 1); binaries near the left peak are formed from scenario A, whereas those near the right peak are from all four scenarios.

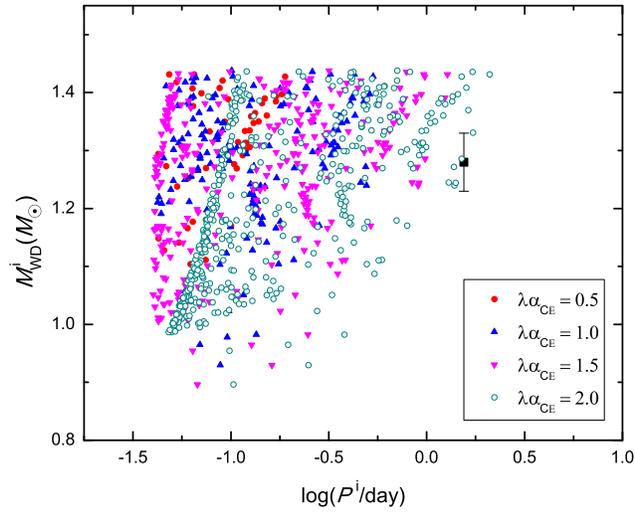


Fig. 2 The initial orbital period and WD mass ($\log P^i$ and M_{WD}^i) distribution of ONe WD + He star systems based on BPS simulations, in which He star mass is constrained between 1.45 and 1.55 M_{\odot} . The dots, triangles, inverted triangles and open circles represent the cases with $\lambda\alpha_{\text{CE}} = 0.5, 1.0, 1.5$ and 2.0, respectively. The black square with an error bar represents HD 49798/RX J0648.0–4418.

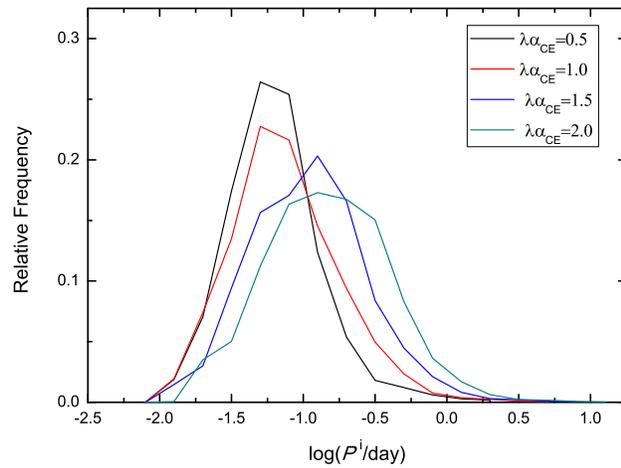


Fig. 3 Distribution of the orbital periods of ONe WD + He star systems with different values of $\lambda\alpha_{\text{CE}}$, in which the mass of He stars is not restricted. The black, red, blue and green lines represent the cases with $\lambda\alpha_{\text{CE}} = 0.5, 1.0, 1.5$ and 2.0, respectively. Here, every case is normalized to be 1.

4 DISCUSSION AND CONCLUSIONS

In this article, we found that there is almost no orbital period as large as HD 49798/RX J0648.0–4418 in these ONe WD + He star systems, which means that the companion of HD 49798 may not

be an ONe WD under our assumptions.² Thus, the ultimate fate of the binary can be constrained to a certain extent. By assuming the compact companion is a CO WD, Wang & Han (2010) recently made an evolutionary investigation of this binary. In their calculations, the optically thick wind model is adopted and the mass accumulation efficiency of the He-shell flash is from Kato & Hachisu (2004). Wang & Han (2010) suggested that about 6×10^4 yr later, the WD companion of HD 49798 will increase its mass to $1.4 M_{\odot}$ and an SN Ia may be produced, leaving a surviving He star as massive as $1.1817 M_{\odot}$. Furthermore, Mereghetti et al. (2009) suggested that the companion of HD 49798 may be a rapidly rotating WD, which would lead to a CO WD more massive than the Chandrasekhar limit (e.g., Yoon & Langer 2005; Chen & Li 2009). From figure 2 of Wang & Han (2010) we can see that the WD companion of HD 49798 could eventually increase its mass to $1.62 M_{\odot}$ when differential rotation cannot be maintained. Thus, we speculate that the companion of HD 49798 may evolve to an overluminous SN Ia.

However, if the companion of HD 49798 is a CO WD, a question would be raised about how such a massive CO WD like the companion of HD 49798 could be formed with almost no mass transfer from the He star before it fills its Roche lobe. HD 49798/RX J0648.0–4418 is considered to be the production of a CE ejection and spiral-in process (e.g., Israel et al. 1997; Bisscheroux et al. 1997). Iben & Tutukov (1993) claimed that HD 49798 was produced from an $8 - 9 M_{\odot}$ progenitor which had filled its Roche lobe before the He-core burning stage. They thought that HD 49798 is currently an He-core burning star (see also Kudritzki & Simon 1978). In contrast, Bisscheroux et al. (1997) argued that the progenitor of HD 49798 was an EAGB star before the CE was formed and currently HD 49798 is at the He-shell burning stage with a CO core in the center. Furthermore, Wang & Han (2010) simulated the evolution of the binary HD 49798/RX J0648.0–4418 and found that the mass of the CO core is about $0.79 M_{\odot}$ at the current position of HD 49798.

The compact companion of HD 49798 might also be a hybrid CONe WD. When the convective boundary mixing is taken into account, a super AGB star may evolve to form a hybrid CONe core with a relatively large unburned CO core (about $0.2 M_{\odot}$), which is surrounded by an ONe zone (greater than $0.85 M_{\odot}$) and a thin CO layer on the surface (Denissenkov et al. 2013). By considering a series of convective Urca shell flashes and some different assumptions about mixing, Denissenkov et al. (2015) found that an explosive carbon ignition would be reached when hybrid CONe WDs approach the Chandrasekhar limit, leading to a low peak luminosity SN Ia because of the low carbon to oxygen ratio. Wang et al. (2014) gave the birthrate of SNe Ia with the CONe WD + He star scenario using a BPS approach. Furthermore, Chen et al. (2014b) suggested that hybrid CONe WDs could be as massive as $1.3 M_{\odot}$ in an extreme case. Thus, the companion of HD 49798, which is as massive as $1.28 M_{\odot}$, may also be a hybrid CONe WD. However, it is still unclear what is the relationship between the mass of the CO core and ONe regions and what is the smallest CO core mass for a thermonuclear explosion to happen. Moreover, the carbon-burning rate, which is still an uncertain parameter, plays an important role in determining the largest possible mass of hybrid CONe WDs (see Chen et al. 2014b). The uncertainties associated with hybrid CONe WDs make it doubtful that such a massive WD like the companion of HD 49798 could be a hybrid CONe WD.

We also note that there are still arguments about the predictive ability of the BPS method. Toonen et al. (2014) recently compared four different BPS codes and found that the differences in their results are not because of numerical effects, but due to different assumptions used in their Monte Carlo simulations (e.g., initial mass function, initial mass ratio distribution, orbital eccentricity distribution, etc). Wang et al. (2009b) compared some initial parameters for producing SNe Ia through the CO WD + He star model. Their work indicates that the initial assumptions adopted in this article may result in a maximum SN Ia birthrate. In this work, we performed four sets of simulations. The results presented here show that a larger value of $\lambda_{\alpha_{\text{CE}}}$ could produce wider and more ONe WD + He star systems. We also presented an extreme case with $\lambda_{\alpha_{\text{CE}}} = 2.0$ and found

² The orbital period of HD 49798/RX J0648.0–4418 can be reproduced by the CO WD + He star model, which has a range of 0.01–5.62 days.

that HD 49798 with its WD companion may be reproduced in the ONe WD + He star model with an extreme value of $\lambda_{\alpha_{\text{CE}}}$, but the probability is very low.

Aside from HD 49798 with its X-ray pulsating companion, another well studied WD + He star system is V445 Pup which was the location of the first detected He nova (Ashok & Banerjee 2003; Kato & Hachisu 2003). The mass of the He star in V445 Pup is about $1.2 - 1.3 M_{\odot}$ derived from the pre-outburst luminosity of the binary (Woudt et al. 2009). Kato et al. (2008) fitted the light curve of the binary and estimated that the mass of the WD companion is larger than $1.35 M_{\odot}$. They also found that almost half of the material accreted from the He star remained on the surface of the WD. Recently, Goranskij et al. (2010) declared that the orbital period of V445 Pup might be 0.65 day. Moreover, the WD companion is more likely to be a CO WD but not an ONe WD since no Neon line was detected in the ejected nebula (e.g., Woudt & Steeghs 2005). Thus, V445 Pup is also a possible candidate of an SN Ia progenitor.

In this article, we performed a series of Monte Carlo BPS simulations with different values of CE ejection parameters. A number of ONe WD + He star systems were obtained and it is very difficult for the companion of HD 49798 to be an ONe WD under our simulations. If we exclude the case of an ONe WD, the companion of HD 49798 may be a CO WD or a COHe hybrid WD, both of which can be expected to evolve to an SN Ia. Because of the rapid rotation of the companion, it is possible to produce an overluminous SN Ia. If the companion of HD 49798 is a CO WD, it would be a challenge for the current binary evolution theory to explain how such a massive CO WD was formed. We hope that this work can stimulate more observations of WD + He star systems so that more detailed studies on the WD + He star channel can proceed.

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