

A likely candidate of type Ia supernova progenitors: the X-ray pulsating companion of the hot subdwarf HD 49798*

Bo Wang^{1,2,3} and Zhan-Wen Han^{1,2}

¹ National Astronomical Observatories / Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China; wangbo@ynao.ac.cn; zhanwenhan@ynao.ac.cn

² Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China

³ Graduate University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract HD 49798 is a hydrogen depleted subdwarf O6 star and has an X-ray pulsating companion (RX J0648.0–4418). The X-ray pulsating companion is a massive white dwarf. Employing Eggleton’s stellar evolution code with the optically thick wind assumption, we find that the hot subdwarf HD 49798 and its X-ray pulsating companion could produce a type Ia supernova (SN Ia) in future evolution. This implies that the binary system is a likely candidate of an SN Ia progenitor. We also discuss the possibilities of some other WD + He star systems (e.g. V445 Pup and KPD 1930+2752) for producing SNe Ia.

Key words: binaries: close — stars: individual: (HD 49798) — stars: evolution — supernovae: general — white dwarfs

1 INTRODUCTION

Type Ia supernova (SN Ia) explosions are among the most energetic events observed in the Universe. They appear to be good cosmological distance indicators owing to their high luminosities and remarkable uniformity, and have been applied successfully in determining cosmological parameters (e.g. Ω_M and Ω_Λ ; Riess et al. 1998; Perlmutter et al. 1999). However, the exact explosion mechanism and the nature of progenitors are still poorly understood (Hillebrandt & Niemeyer 2000; Podsiadlowski 2010; Wang et al. 2008a, 2010b), and no SN Ia progenitor system before the explosion has been conclusively identified (Wang & Han 2009, 2010a; Meng & Yang 2010a).

It is widely accepted that SNe Ia arise from thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) in binaries (Nomoto et al. 1997; Livio 2000). Over the past few decades, two types of SN Ia progenitor models have been proposed, i.e. the double-degenerate (DD) and single-degenerate (SD) models. The DD model involves the merger of two CO WDs (Tutukov & Yungelson 1981; Iben & Tutukov 1984; Webbink 1984; Han 1998). Although the DD model might be able to

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account for the explosion of a few overluminous SNe Ia (Howell et al. 2006; Gilfanov & Bogdán 2010), it is still suffering from the theoretical difficulty that the mergers of two WDs may lead to an accretion-induced collapse rather than a thermonuclear explosion (Nomoto & Iben 1985; Saio & Nomoto 1985; Timmes et al. 1994). For the SD model, the companion could be a main-sequence (MS) star or a slightly evolved star (WD + MS channel), or a red-giant star (WD + RG channel) (Hachisu et al. 1996; Li & van den Heuvel 1997; Langer et al. 2000; Fedorova et al. 2004; Han & Podsiadlowski 2004, 2006; Chen & Li 2007; Ruiter et al. 2009; Lü et al. 2009; Meng & Yang 2010b; Wang et al. 2010a; Wang & Han 2010b). Observationally, there is increasing evidence indicating that at least some SNe Ia may come from the SD model (Hansen 2003; Ruiz-Lapuente et al. 2004; Voss & Nelemans 2008; Wang et al. 2008b; Justham et al. 2009). Moreover, the detections of variable Na I D lines (Patat et al. 2007; Blondin et al. 2009; Simon et al. 2009) and derivation of a smaller absorption ratio R_V that is characteristic of circumstellar material (CSM) dust (Wang et al. 2009c), perhaps suggests the presence of CSM around a subclass of SNe Ia.

Recently, Wang et al. (2009a) studied the WD + He star channel of the SD model that produces SNe Ia, in which a CO WD accretes material from an He MS star or a slightly evolved He star to increase its mass to the Chandrasekhar (Ch) mass. The study derived the parameter spaces for the progenitors of SNe Ia. By using a detailed binary population synthesis approach, Wang et al. (2009b) found that the Galactic SN Ia birthrate from this channel is $\sim 0.3 \times 10^{-3} \text{ yr}^{-1}$, and that this channel may account for SNe Ia with short delay times ($\sim 45\text{--}140 \text{ Myr}$) from the star formation to the SN explosion (see also Wang & Han 2010c).

Hot subdwarf stars are near the blue end of the horizontal branch in the Hertzsprung-Russell diagram. A particularly interesting member of this class is a subdwarf O star, HD 49798, which is one of the brightest subdwarfs and also a single-lined spectroscopic binary with an orbital period of 1.548 d (Thackeray 1970; Stickland & Lloyd 1994). This hydrogen-deficient subdwarf of spectral type O6 has been studied extensively (Kudritzki & Simon 1978; Hamann et al. 1981). Bisscheroux et al. (1997) showed that the hot subdwarf star HD 49798 must have a degenerate C-O core, and is in the He-shell burning phase, which can explain its high luminosity. Israel et al. (1997) reported the detection of a pulsating soft X-ray source (RX J0648.0–4418) with a pulsation period of $\sim 13 \text{ s}$ from this binary. The X-ray spectrum of the source is very soft, but has a high-energy excess. The discovery of the regular X-ray pulsations must arise from a compact companion of either a neutron star or a WD (e.g. Israel et al. 1997; Bisscheroux et al. 1997). Bisscheroux et al. (1997) excluded a neutron star as the companion of HD 49798, and showed that all observations are consistent with a weakly magnetized massive WD, which is accreting material from the wind of its subdwarf companion.

Kudritzki & Simon (1978) estimated a mass of $0.7\text{--}2.7 M_{\odot}$ for the hot subdwarf HD 49798. This system is consistent with a double spectroscopic binary, favored by the detection of a fast X-ray pulsar source, for which all the orbital parameters (including the masses of the two components) may be derived. With this purpose, Mereghetti et al. (2009) recently observed HD 49798/RX J0648.0–4418 in May 2008 with the XMM-Newton satellite. They confirmed that the 13 s pulsation in the X-ray binary HD 49798/RX J0648.0–4418 is due to a rapidly rotating WD. From the pulse time delays and the system's inclination, constrained by the duration of the X-ray eclipse discovered in this observation, they derived the masses of the two components. The corresponding masses are $1.50 \pm 0.05 M_{\odot}$ for HD 49798 and $1.28 \pm 0.05 M_{\odot}$ for the WD.

The existence of WD + He star systems is supported by some observations (Wang et al. 2009a). The hot subdwarf HD 49798 with its WD companion is such a system, and may be a candidate of SN Ia progenitors. The goal of this paper is to investigate the evolution and final fate of the hot subdwarf HD 49798 and its WD companion, and to explore whether this binary system could produce an SN Ia. In Section 2, we describe the numerical code of the binary evolution and the input physics. In Section 3, we give the binary evolutionary results. Finally, discussion and conclusions are given in Section 4.

2 BINARY EVOLUTION CALCULATIONS

We use Eggleton's stellar evolution code (Eggleton 1971, 1972, 1973) to calculate the evolution of the hot subdwarf HD 49798 and its WD companion. The code has been updated with the latest input physics over the last four decades (Han et al. 1994; Pols et al. 1995, 1998). Roche lobe overflow (RLOF) is treated within the code as 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 Guo et al. (2008). To simplify our calculations, the He star was assumed to have an He abundance $Y = 0.98$ and metallicity $Z = 0.02$. We assume that the binary model starts with a $1.5 M_\odot$ He star and a $1.28 M_\odot$ CO WD having a 1.548 d orbital period, similar to the initial model of HD 49798 and its WD companion.

Instead of solving stellar structure equations of the WD, we use the optically thick wind model (Hachisu et al. 1996) and adopt the prescription of Kato & Hachisu (2004, KH04) for the mass-accumulation efficiency of He-shell flashes onto the WD. If the mass-transfer rate, $|\dot{M}_2|$, is above a critical rate, \dot{M}_{cr} , we assume that He burns steadily on the surface of the WD and that the He-rich matter is converted into C and O at a rate \dot{M}_{cr} . The unburned matter is lost from the system, presumably in the form of the optically thick wind at a mass-loss rate $\dot{M}_{\text{wind}} = |\dot{M}_2| - \dot{M}_{\text{cr}}$. The critical mass-transfer rate is

$$\dot{M}_{\text{cr}} = 7.2 \times 10^{-6} (M_{\text{WD}}/M_\odot - 0.6) M_\odot \text{yr}^{-1}, \quad (1)$$

based on WD models computed with constant mass-accretion rates (Nomoto 1982). Similar to the work of Wang et al. (2009a), the following assumptions are adopted when $|\dot{M}_2|$ is smaller than \dot{M}_{cr} (see also Wang & Han 2010d):

- (1) If $|\dot{M}_2|$ is less than \dot{M}_{cr} but higher than the minimum accretion rate of stable He-shell burning, \dot{M}_{st} (KH04), it is assumed that the He-shell burning is stable and that there is no mass loss.
- (2) If $|\dot{M}_2|$ is less than \dot{M}_{st} but higher than the minimum accretion rate of weak He-shell flashes, $\dot{M}_{\text{low}} = 4.0 \times 10^{-8} M_\odot \text{yr}^{-1}$ (Woosley et al. 1986), He-shell flashes occur and part of the envelope's mass is assumed to be blown off from the surface of the WD. The WD mass-growth rate in this case is linearly interpolated from a grid computed by KH04, where a wide range of WD masses and accretion rates can be calculated in the He-shell flashes.
- (3) If $|\dot{M}_2|$ is lower than \dot{M}_{low} , the He-shell flashes will be so strong that no mass can be accumulated onto the WD.

We define the mass-growth rate of the CO WD, \dot{M}_{CO} , as

$$\dot{M}_{\text{CO}} = \eta_{\text{He}} |\dot{M}_2|, \quad (2)$$

where η_{He} is the mass-accumulation efficiency for the He-shell burning. According to the assumptions above, the values of η_{He} are:

$$\eta_{\text{He}} = \begin{cases} \frac{\dot{M}_{\text{cr}}}{|\dot{M}_2|}, & |\dot{M}_2| > \dot{M}_{\text{cr}}, \\ 1, & \dot{M}_{\text{cr}} \geq |\dot{M}_2| \geq \dot{M}_{\text{st}}, \\ \eta'_{\text{He}}, & \dot{M}_{\text{st}} > |\dot{M}_2| \geq \dot{M}_{\text{low}}, \\ 0, & |\dot{M}_2| < \dot{M}_{\text{low}}. \end{cases} \quad (3)$$

We incorporated the prescriptions above into Eggleton's stellar evolution code and followed the evolution of the WD + He star system. The mass lost from the system via the optically thick wind is assumed to take away specific orbital angular momentum from the He-accreting WD. We also consider the mass-loss from the stellar wind of the He star, which is assumed to take away specific

orbital angular momentum from the He star. This mass-loss of the He star from the stellar wind is considered to be

$$\log \dot{M}_{\text{wind}} = 1.5 \log L/L_{\odot} - 14.4, \quad (4)$$

based on the stellar wind analysis from subdwarf O stars (including He stars) to massive O stars (Jeffery & Hamann 2010). We assume that, if the WD grows to $1.4 M_{\odot}$, it explodes as an SN Ia. Finally, we have calculated the evolution of the WD + He star system, and found that this binary system could produce an SN Ia.

3 BINARY EVOLUTION RESULTS

The WD + He star system starts with $(M_2^i, M_{\text{WD}}^i, \log(P^i/\text{day})) = (1.50, 1.28, 0.19)$, where M_2^i and M_{WD}^i are the initial masses of the He star and of the CO WD in solar masses respectively, and P^i is the initial orbital period in days. Figure 1 shows the evolutionary track of the He donor star and the evolution of the orbital period, where the current position of HD 49798 is also indicated. Figure 2 displays \dot{M}_2 , \dot{M}_{CO} and \dot{M}_{WD} varying with time after HD 49798 fills its Roche lobe.

The He star undergoes the He-core burning for about seven million years. After the exhaustion of the central helium, the envelope of the He star expands. When the radius of the He star reaches $1.45 R_{\odot}$ (Bisscheroux et al. 1997), the He star evolves to the current position of HD 49798. At this point, the CO core mass of the He star reaches $0.79 M_{\odot}$, and the logarithmic temperature and luminosity are 4.67 and 3.97, respectively, which are consistent with the parameters of HD 49798

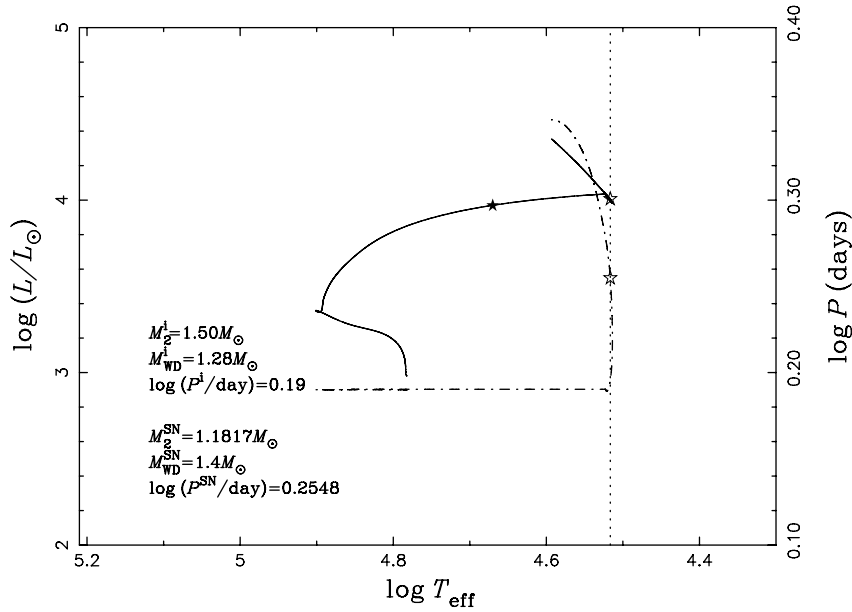


Fig. 1 Results of binary evolution calculations with initial masses of two components and the orbital period as well, which are similar to the binary system HD 49798/RX J0648.9–4418. The evolutionary track of the He donor star is shown as a solid curve, and the evolution of the orbital period is shown as a dash-dotted curve. The solid star represents the current position of HD 49798. The dotted vertical line and these two open stars indicate the position where the WD is expected to explode as an SN Ia. The initial binary parameters and the parameters at the moment of the SN explosion are given in the lower left corner of this figure.

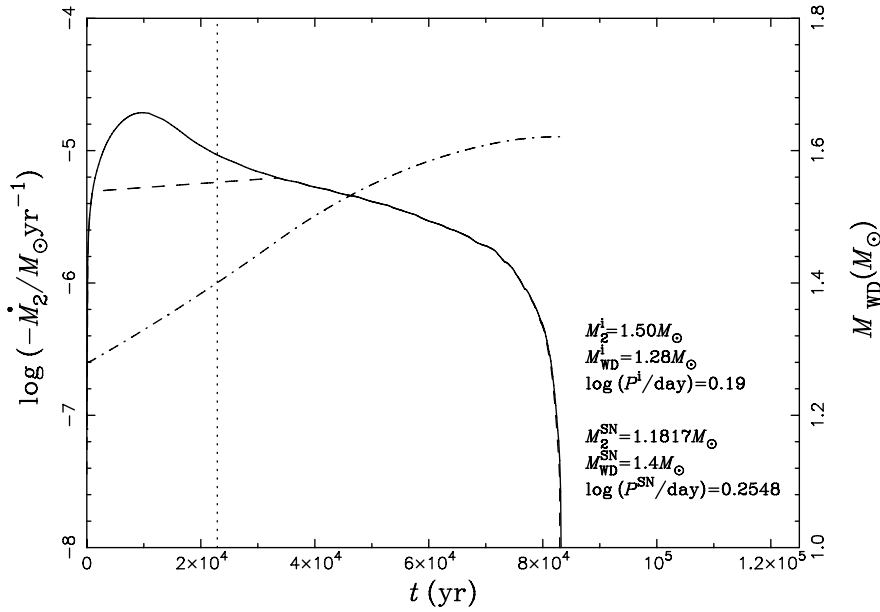


Fig. 2 Results of binary evolution calculations, but for \dot{M}_2 (solid curve), \dot{M}_{CO} (dashed curve) and M_{WD} (dash-dotted curve) varying with time after HD 49798 fills its Roche lobe. The dotted vertical line indicates the position where the WD is expected to explode as an SN Ia.

derived from the detailed spectral analysis (see Bisscheroux et al. 1997). After about 4×10^4 yr, HD 49798 begins to fill its Roche lobe due to the rapid expansion of its envelope. The mass-transfer rate $|\dot{M}_2|$ exceeds \dot{M}_{cr} soon after the onset of RLOF, leading to a wind phase. In this phase, a part of the transferred mass is blown off in the form of the optically thick wind, and the remaining part accumulates onto the WD. The WD increases its mass to $1.4 M_{\odot}$ after about 2×10^4 yr and explodes as an SN Ia. At this moment, the mass of the He star is $M_2^{\text{SN}} = 1.1817 M_{\odot}$ and the orbital period is $\log(P^{\text{SN}}/\text{day}) = 0.2548$.

4 DISCUSSION AND CONCLUSIONS

The observations indicate that the X-ray source (RX J0648.0–4418) is a weakly magnetized massive WD which is accreting matter from the wind of its subdwarf companion. The mass loss of HD 49798 from the wind in our calculations is about $3 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$. By using the Bondi-Hoyle formalism as described by Davidson & Ostriker (1973), we can estimate the mass M_{acc} captured from the wind by the gravitational field of the WD, and the luminosity L_{acc} converted by the potential energy in the process of accretion. We find that a wind velocity between $800\text{--}1350 \text{ km s}^{-1}$ with $M_{\text{wind}} = 3 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ will result in an accretion luminosity between $10^{30} - 10^{31} \text{ erg s}^{-1}$, consistent with that of the observed X-ray luminosity $\sim 10^{31} \text{ erg s}^{-1}$ in the $0.2\text{--}10 \text{ keV}$ energy range (e.g. Mereghetti et al. 2009).

Mereghetti et al. (2009) confirmed that RX J0648.0–4418 is a rapidly rotating WD. The maximum stable mass of a rotating WD may be above the standard Chandrasekhar (Ch) mass (e.g. Uenishi et al. 2003; Yoon & Langer 2005; Chen & Li 2009), and the maximum possible mass a CO WD can reach by mass accretion is about $2.0 M_{\odot}$ (see Yoon & Langer 2005). According to our calculations, the maximum mass that the WD RX J0648.0–4418 can reach is about $1.62 M_{\odot}$ (see

Fig. 2), which is larger than the standard Ch mass ($1.4 M_{\odot}$) that we set in this paper. Thus, we point out that the WD companion of HD 49798 might evolve towards a thermonuclear explosion of the super-Ch mass WD, producing an overluminous SN Ia (e.g. Howell et al. 2006). We also note that, if rotation is taken into account, He burning is much less violent than that without rotation (see Yoon et al. 2004). This may significantly increase the He-accretion efficiency (i.e. η_{He} in our parametrization). Therefore, more He-rich matter can be converted into C and O, increasing the chance for a WD to survive above the Ch mass limit.

The process that leads to the formation of this peculiar system is still poorly understood. It is suggested that HD 49798/RX J0648.0–4418 corresponds to a previously unobserved evolutionary stage of a massive binary system, after the common-envelope phase and spiral-in (e.g. Israel et al. 1997; Bisscheroux et al. 1997). A primordial binary system with a primary mass $M_{1,i} \sim 5.0 - 8.0 M_{\odot}$ and a secondary mass $M_{2,i} \sim 2.0 - 6.5 M_{\odot}$ may produce a system like HD 49798 and its WD companion (Wang et al. 2009b). We note that the primordial binary system has a short delay time (~ 100 Myr) from the star formation to the SN explosion. Thus, HD 49798 and its WD companion can contribute to the young population of SNe Ia revealed by recent observations (Mannucci et al. 2006; Aubourg et al. 2008). The young population of SNe Ia may have an effect on models of galactic chemical evolution, since they would return large amounts of iron to the interstellar medium much earlier than previously thought.

The WDs usually have masses in a narrow range centered at about $0.6 M_{\odot}$ (Kepler et al. 2007). However, a few examples of WDs with very high masses ($> 1.2 M_{\odot}$) have recently been reported (Dahn et al. 2004; Vennes & Kawka 2008). Also, the X-ray source RX J0648.9–4418 may be such a massive WD. These massive WDs in binary systems are good candidates for the formation of SNe Ia if the mass transfer can occur, since a small amount of accreted mass could drive them above the Ch mass limit.

Besides HD 49798 and its WD companion, there are also some other WD + He star systems, e.g. V445 Pup and KPD 1930+2752, which are also good candidates of SN Ia progenitors. V445 Pup is an He nova (Ashok & Banerjee 2003; Kato & Hachisu 2003). Kato et al. (2008) recently presented a free-free emission dominated light curve model of V445 Pup, based on the optically thick wind theory (Hachisu et al. 1996). The light curve fitting showed that the mass of the WD is above $1.35 M_{\odot}$, and half of the accreted matter remains on the WD, resulting in the mass increase of the WD. Thus, V445 Pup is suggested to be one of the best candidates for SN Ia progenitors (Kato et al. 2008; see also Woudt et al. 2009). However, the orbital period of the binary system and the mass of the He star are still uncertain so far. To clarify the above parameters, further observations of V445 Pup are needed when the dense dust shell disappears. KPD 1930+2752 is regarded as another candidate for a SN Ia progenitor, giving rise to an SN Ia explosion in the form of merging WDs (Maxted et al. 2000; Geier et al. 2007). Note that, the DD model is not supported theoretically, as it may lead to an accretion-induced collapse rather than to an SN Ia (Nomoto & Iben 1985; Saio & Nomoto 1985; Timmes et al. 1994). On the other hand, KPD 1930+2752 may also produce an SN Ia through the SD model. However, the mass of the He donor star in KPD 1930+2752 is limited to the range between $0.45 M_{\odot}$ and $0.52 M_{\odot}$ (Geier et al. 2007), which is below the minimum mass ($0.95 M_{\odot}$) for producing SNe Ia (Wang et al. 2009a). Thus, KPD 1930+2752 may not be a good candidate to produce an SN Ia via the SD model.

In this paper, by using the optically thick wind model (Hachisu et al. 1996) and adopting the prescription of KH04 for the mass accumulation efficiency of the He-shell flashes onto the WD, we showed that the hot subdwarf HD 49798 and its X-ray pulsating companion could produce an SN Ia in future evolution. We also discussed the possibilities of some other WD + He star systems for producing SNe Ia. To further study the WD + He star channel of SNe Ia, large samples of WD + He star systems are expected in future observations.

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