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Past and future of the central double-degenerate core of Henize 2–428

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Abstract It has been suggested that Type Ia supernovae (SNe Ia) could be produced in the conditions of the violent merger scenario of the double-degenerate model, in which a thermonuclear explosion could be produced when a double carbon-oxygen white dwarf (CO WD) merges. It has been recently found that the nucleus of the bipolar planetary nebula Henize 2–428 consists of a double CO WD system that has a total mass of $\sim 1.76\,M_{\odot}$, a mass ratio of ~ 1 and an orbital period of $\sim 4.2\,\mathrm{h}$, which is the first and only discovered progenitor candidate for an SN Ia predicted by the violent merger scenario. In this work, we aim to reproduce the evolutionary history of the central double CO WD of Henize 2–428. We find that the planetary nebula Henize 2–428 may originate from a primordial binary that has a $\sim 5.4\,M_{\odot}$ primary and a $\sim 2.7\,M_{\odot}$ secondary with an initial orbital period of $\sim 15.9\,\mathrm{d}$. The double CO WD was formed after the primordial binary experienced two Roche-lobe overflows and two common-envelope ejection processes. According to our calculations, it takes about $\sim 840\,\mathrm{Myr}$ for the double CO WD to merge and form an SN Ia driven by gravitational wave radiation after their birth. To produce the current status of Henize 2–428, a large common-envelope parameter is needed. We also estimate that the rate of SNe Ia from the violent merger scenario is at most $2.9 \times 10^{-4}\,\mathrm{yr}^{-1}$, and that the delay time is in the range of $\sim 90\,\mathrm{Myr}$ to the Hubble time.

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

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are one of the most luminous phenomena in the Universe. They have been used as standard candles for measuring cosmological distances. By employing the correlation between the maximum luminosity and the light curve width of SNe Ia (e.g., Phillips 1993), it has been found that the expansion of the Universe is accelerating (e.g., Riess et al. 1998; Perlmutter et al. 1999). SNe Ia may also have a great influence on the chemical evolution of their host galaxies due to the production of iron-peak elements during SN Ia explosions (e.g., Greggio & Renzini 1983; Matteucci & Greggio 1986; Li et al. 2018). In addition, cosmic rays may be accelerated by SN remnants (e.g., Fang & Zhang 2012; Yang et al. 2015). However, the progenitor models for SNe Ia are still under discussion, which may influence the accuracy of measuring cosmological distances (e.g., Podsiadlowski et al. 2008; Howell 2011; Liu et al. 2012; Wang & Han 2012; Wang et al. 2013; Maoz et al. 2014; Wang 2018).

It has been suggested that SNe Ia are the thermonuclear explosions of carbon-oxygen white dwarfs (CO WDs) in close binaries (e.g., Hoyle & Fowler 1960). There are two kinds of competing progenitor models of SNe Ia discussed frequently, i.e., the single-degenerate (SD) model and the double-degenerate (DD) model. In the SD model, a WD accretes material from a non-degenerate companion and explodes as an SN Ia when its mass approaches the Chandrasekhar mass limit (e.g. Whelan & Iben 1973; Nomoto et al. 1984). In the SD model, the companion could be a main sequence (MS) star, a red giant branch (RGB) star or a helium (He) star (e.g., Li & van den

Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004, 2006; Wang et al. 2009b; Ablimit et al. 2014; Wu et al. 2016; Liu et al. 2017a). In the DD model, SNe Ia arise from the merging of double CO WDs that have a total mass larger than the Chandrasekhar mass limit (e.g., Webbink 1984; Iben & Tutukov 1984), though some studies have argued that double WD mergers with sub-Chandrasekhar mass may also produce SNe Ia (e.g., Ji et al. 2013; Liu et al. 2017b). Comparing with the SD model, the rate of SNe predicted by the DD model is high enough to satisfy observational results (e.g., Yungelson et al. 1994; Han 1998; Nelemans et al. 2001; Ruiter et al. 2009; Liu et al. 2018). The delay time of an SN Ia is defined as the time interval between the formation of the primordial binary to the moment when the SN Ia explodes. The delay time distributions (DTDs) predicted by the DD model roughly follow a single power law, which is similar to that derived by observations (e.g., Maoz et al. 2011; Ruiter et al. 2009; Mennekens et al. 2010; Yungelson & Kuranov 2017; Liu et al. 2018). However, some studies show that the merger of double CO WDs may produce accretion induced collapse SNe and eventually form neutron stars (Nomoto & Iben 1985; Saio & Nomoto 1985; Timmes et al. 1994).

It has been proposed that an instantaneous explosion could be triggered while the merging process of double CO WDs is still ongoing, triggering an SN Ia (see Pakmor et al. 2010, 2011, 2012). This is a subclass of the DD model named the violent merger scenario. Pakmor et al. (2010) found that the violent mergers of two $0.9\,M_\odot$ CO WDs may produce 1991bg-like events. Pakmor et al. (2011) suggested that the critical minimum mass ratio of double CO WDs for producing an SN Ia is $0.8\,M_\odot$ based on the violent merger scenario. Röpke et al. (2012) found that the violent merger scenario could also explain the observational properties of SN 2011fe. Sato et al. (2016) simulated a large sample of double CO WDs and found that the critical minimum mass of each WD for producing SNe Ia is $0.8\,M_\odot$ based on the violent merger scenario. Liu et al. (2016) systematically investigated the violent merger scenario by considering the WD+He subgiant channel for the formation of double massive WDs and found that the WD+He subgiant channel may contribute to about 10% of all SNe Ia in the Galaxy based on the violent merger scenario.

Henize 2–428, a bipolar planetary nebula (PN G049.4+02.4), is $\sim 1.4 \pm 0.4\,\mathrm{kpc}$ from the solar system (see Santander-García et al. 2015). By assuming that the double He II 541.2 nm line profile is caused by the absorption of binaries, Santander-García et al. (2015) analyzed the light curves of Henize 2–428, and found that its nucleus consists of two nearly-equal-mass CO WDs. The total mass of this system is $\sim 1.76\,M_\odot$ and the orbital period is $\sim 4.2\,\mathrm{h}$. According to the violent merger scenario, the DD cores of Henize 2–428 make a strong candidate for a progenitor of an SN Ia. However, the formation path to the nucleus of Henize 2–428 is still unknown.

In this work, we aim to investigate the evolutionary history of the bipolar planetary nebula Henize 2–428, and provide the rates and DTDs of SNe Ia from the violent merger scenario. In Section 2, we introduce our numerical methods. We present the results and discussion in Section 3. To finish, we provide a summary in Section 4.

2 NUMERICAL METHODS

2.1 Violent Merger Criteria

The merging of double WDs could trigger prompt detonation and produce SNe Ia under certain conditions. In this work, we assume that the criteria for violent WD mergers are as follows:

(1) The mass ratio of double CO WDs ($q = M_{\rm WD2}/M_{\rm WD1}$) should be larger than 0.8, where $M_{\rm WD1}$ is the mass of the more-massive WD, and $M_{\rm WD2}$ the mass of the less-massive one (see Pakmor et al. 2011; Liu et al. 2016).
(2) The critical minimum mass of each WD is assumed to be $0.8\,M_\odot$ (Sato et al. 2016).
(3) The delay times of SNe Ia should be less than the Hubble time, i.e., $t = t_{\rm evol} + t_{\rm GW} \leq t_{\rm Hubble}$, where $t_{\rm evol}$ is the evolutionary timescale from primordial binaries to the formation of double CO WDs, and $t_{\rm GW}$ is the timescale during which double WDs are brought together by gravitational wave radiation, written as

$$t_{\rm GW} = 8 \times 10^7 \times \frac{(M_{\rm WD1}+M_{\rm WD2})^{1/3}}{M_{\rm WD1}M_{\rm WD2}} P^{8/3}, \qquad (1)$$

in which $t_{\rm GW}$ is in the unit of years, P is the orbital period of double WDs in hours, and $M_{\rm WD1}$ and $M_{\rm WD2}$ are in the units of $M_\odot$.

By adopting these criteria, we obtained a large number of double CO WD systems that may merge violently and then explode as SNe Ia. Subsequently, we provide the evolutionary path of the double WDs closest to the current parameters of Henize 2–428 in order to approximate the evolutionary history of Henize 2–428 and speculate on its fate.

2.2 BPS Approaches

By employing the rapid binary evolutionary code (Hurley et al. 2000, 2002), we performed a series of Monte Carlo binary population synthesis (BPS) simulations evolving primordial binaries to the merging of double CO WDs. In each simulation, 2×10^7 primordial binaries are calculated. The initial parameters and basic assumptions in our Monte Carlo BPS computations listed below are adopted:

(1) The initial metallicity in our simulations is set to be 0.02.
(2) We assume that all stars are in binaries with circular orbits.
(3) The initial mass function from Miller & Scalo (1979) is adopted for the primordial primaries.
(4) The initial mass ratios ($q' = M_2/M_1$) are assumed to be distributed uniformly (e.g., Mazeh et al. 1992; Goldberg & Mazeh 1994), i.e., $n(q') = 1$, in which $0 \leq q' \leq 1$.
(5) The distribution of initial separation a is assumed to be constant in $\log(a)$ for wide binaries and falls smoothly for close binaries (e.g., Han et al. 1995).
(6) The star formation rate is assumed to be constant ($5\,M_\odot\,\mathrm{yr}^{-1}$) to approximate the Galaxy over the past 15 Gyr (see Yungelson & Livio 1998; Willems & Kolb 2004; Han & Podsiadlowski 2004), or modeled as a delta function (a single starburst of $10^{10}\,M_\odot$ in stars) to roughly describe elliptical galaxies.

2.3 Common Envelope Computation

Common envelope (CE) evolution plays a critical role in the formation of double WDs. However, the prescription for calculating CE ejection is still under debate (e.g. Ivanova et al. 2013). In this work, we adopt the standard energy perspective to simulate the CE ejection process (see Webbink 1984), written as

$$\alpha_{\rm CE}\left(\frac{GM^{\rm f}_{\rm don}M^{\rm f}_{\rm acc}}{2a_{\rm f}} - \frac{GM^{\rm i}_{\rm don}M^{\rm i}_{\rm acc}}{2a_{\rm i}}\right) = \frac{GM^{\rm i}_{\rm don}M_{\rm env}}{\lambda R_{\rm don}}, \tag{2}$$

in which G, $M_{\rm don}$, $M_{\rm acc}$, a, $M_{\rm env}$ and $R_{\rm don}$ are the gravitational constant, donor mass, accretor mass, orbital separation, mass of the donor's envelope and donor radius, respectively. The superscripts i and f stand for these values before and after the CE ejection respectively. From this prescription, we can see that there are two variable parameters, i.e. the CE ejection efficiency ($\alpha_{\rm CE}$) and a stellar structure parameter (λ). These two parameters may change with the evolutionary process (e.g., Ablimit et al. 2016). It has been suggested that the value of $\alpha_{\rm CE}$ may vary with WD mass, secondary mass, mass ratio or orbital period (e.g., De Marco et al. 2011; Davis et al. 2012). Meanwhile,

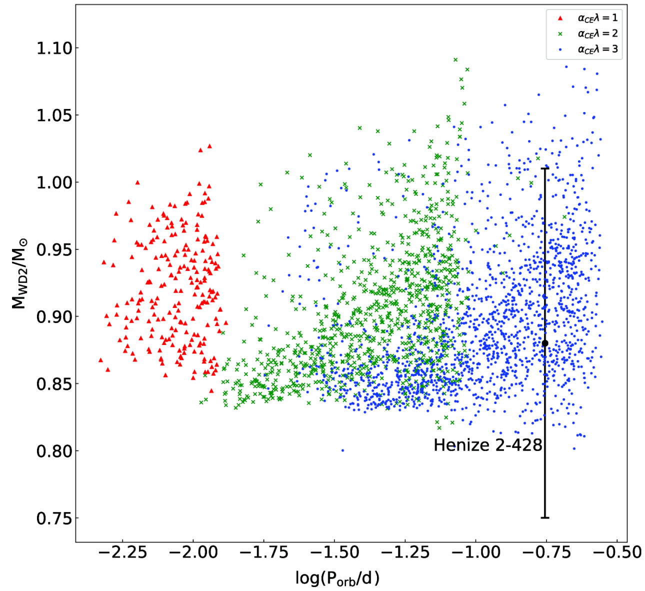

Fig. 1 The distribution of violent WD mergers that can produce SNe Ia in the orbital period−secondary mass ($\log P_{\rm orb} - M_{\rm WD2}$) plane. *Red triangles*, *green crosses* and *blue dots* represent the simulated results with $\alpha_{\rm CE}\lambda = 1, 2$ and 3, respectively. The *filled circle* with error bar represents the position of the central DD cores of Henize 2–428 (Santander-García et al. 2015).

the values of λ could be investigated by considering gravitational energy only, adding internal energy or adding the entropy of the envelope (e.g., Davis et al. 2010; Xu & Li 2010). However, the values of $\alpha_{\rm CE}$ and λ are still highly uncertain. In the present work, similar to our previous studies (e.g., Wang et al. 2009a), we simply combine these two parameters into a single free one (i.e. $\alpha_{\rm CE}\lambda$) based on Equation (2), and assume $\alpha_{\rm CE}\lambda = 1$, 2 and 3 to check its effect on the final results.

3 RESULTS AND DISCUSSION

Figure 1 presents the distribution of double CO WDs that can produce SNe Ia via the violent merger scenario in the $\log P_{\rm orb} - M_{\rm WD2}$ plane. We find that as the value of $\alpha_{\rm CE}\lambda$ increases, the distribution of orbital periods becomes wider and more double WDs would be produced. The reason is that a larger value of $\alpha_{\rm CE}\lambda$ means that less orbital energy would be used for unbinding CE and ejection of the CE would more easily occur. The nucleus of Henize 2–428 consists of two nearly-equal-mass $0.88 \pm 0.13\,M_\odot$ CO WDs and their orbital period is $\sim 4.2\,$h (Santander-García et al. 2015). In this figure, we also show the position of the central DD nucleus of Henize 2–428. Note that for the case of $\alpha_{\rm CE}\lambda = 3$, the parameters of several formed double WDs fall within the range of the observation error of Henize 2–428. We adopted the double WDs that are closest

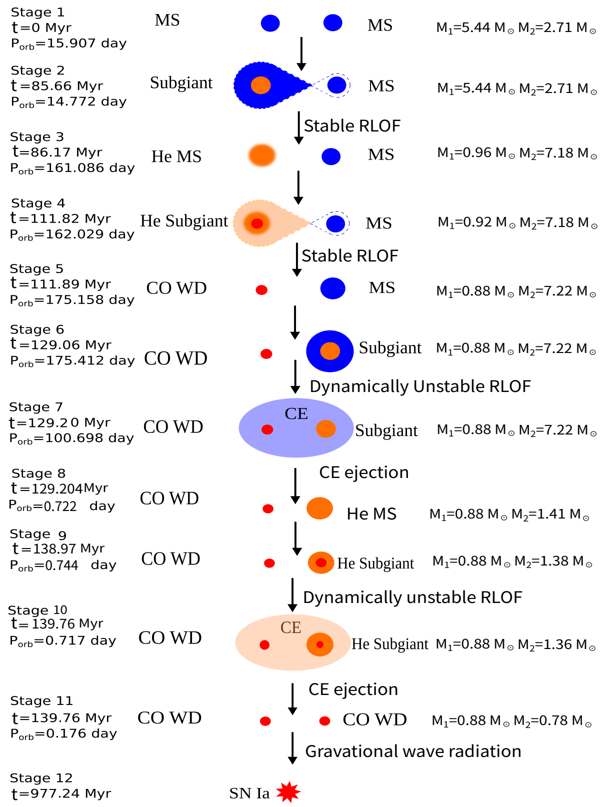

Fig. 2 The evolutionary history and future of the planetary nebula Henize 2–428.

to the current parameters of Henize 2–428 to approximate the evolutionary path of Henize 2–428 (see Fig. 2).

Figure 2 shows the evolutionary path of Henize 2–428. The primordial binary consists of a $5.4\,M_\odot$ primary and a $2.7\,M_\odot$ secondary, with an initial orbital period of $\sim 15.9\,\mathrm{d}$. The primordial primary evolved to a subgiant after about $85.47\,\mathrm{Myr}$. The radius of the primary reaches $22.39\,\mathrm{R}_\odot$ and fills its Roche lobe at $t = 85.67\,\mathrm{Myr}$ (Stage 2), resulting in a stable mass-transfer process. After about $0.5\,\mathrm{Myr}$, the H-rich shell of the primordial primary is exhausted and the mass transfer stops. In this case, the primordial primary becomes a $0.97\,M_\odot$ He MS star and the primordial secondary turns into a $7.18\,M_\odot$ MS star (Stage 3). The orbital period at this stage is $\sim 162\,\mathrm{d}$. At $t = 111.82\,\mathrm{Myr}$, the primordial primary becomes a He subgiant with a radius of $54.95\,R_\odot$ and fills its Roche lobe again, leading to another stable mass-transfer process (Stage 4). When the He-rich shell of the primordial primary is exhausted, the binary evolves to a $0.88\,M_\odot$ CO WD and a $7.22\,M_\odot$ MS star with an orbital period of $175\,\mathrm{d}$ (Stage 5). Subsequently, the primordial secondary continues to evolve, and will fill its Roche lobe when it becomes a subgiant star with a radius of $102.8\,R_\odot$ at $t = 129.06\,\mathrm{Myr}$ (Stage 6). At this stage, the mass transfer is dynamically unstable, leading to the formation of the first CE (Stage 7). After CE ejection, the orbital period shrinks to $0.722\,\mathrm{d}$, and the primordial secondary becomes a $1.43\,M_\odot$ He star (Stage 8). The He star continues to evolve, and will fill its Roche-lobe again after it evolves to the He subgiant stage at about $t = 140\,\mathrm{Myr}$ (Stage 9). At this stage, a CE would be formed due to the dynamically unstable mass-transfer (Stage 10). After the CE ejection, the binary becomes a double WD with nearly-equal mass, in which $M_{\rm WD1} = 0.88\,M_\odot$ and $M_{\rm WD2} = 0.78\,M_\odot$. During this process, the orbital period shrinks to $0.716\,\mathrm{d}$ (Stage 11). The double WD that is formed fits well with the observed parameters of Henize 2–428, i.e., the evolutionary history of Henize 2–428 is reproduced. Previous works on the shapes of nebulae have revealed that a bipolar nebula originates from the CE ejection process (e.g., Han et al. 1995). According to our calculations, we found that the bipolar planetary nebula Henize 2-428 may evolve from the binary in the CE phase with two CO cores. Afterwards, the double WD will later merge, driven by gravitational wave radiation, in $838\,\mathrm{Myr}$, resulting in the production of an SN Ia via the violent merger scenario at about $t = 977\,\mathrm{Myr}$ (Stage 12).

Figure 3 shows the evolution of SN Ia Galactic rates based on the violent merger scenario. In this figure, we adopt a constant star formation rate of $5\,M_\odot\,\mathrm{yr}^{-1}$. From

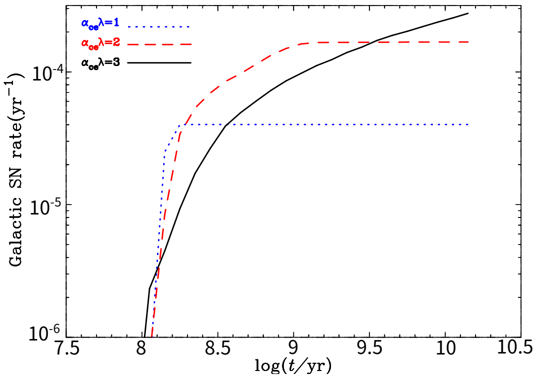

Fig. 3 Evolution of SN Ia rates in the Galaxy based on the violent merger scenario. Here, we adopt a constant star formation rate of $5\,M_\odot\,\mathrm{yr}^{-1}$. The *blue dotted*, *red dashed* and *black solid curves* correspond to cases with $\alpha_{\rm CE}\lambda = 1$, 2 and 3, respectively.

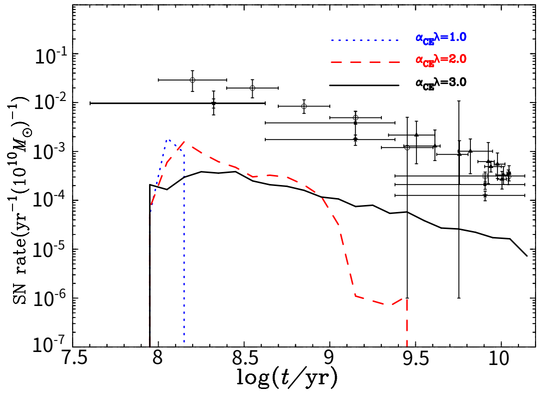

Fig. 4 Similar to Fig. 3, but for the DTDs of SNe Ia. Here, we adopt a starburst of $10^{10}\,M_\odot$ in stars. The *open circles* are from Totani et al. (2008), the *filled triangles* and *squares* are taken from Maoz et al. (2011, 2014) and the *open square* is from Graur & Maoz (2013).

this figure, we can see that the Galactic rates of SNe Ia range from $0.4\times10^{-4}\,\mathrm{yr}^{-1}$ to $2.9\times10^{-4}\,\mathrm{yr}^{-1}$. In observations, the Galactic SN Ia rate is about $3-4\times10^{-3}\,\mathrm{yr}^{-1}$, that is, the violent merger scenario may contribute to about 1%–10% of all SNe Ia in the Galaxy. Note that the rate increases with the value of $\alpha_{\rm CE}\lambda$. That is because, for the case with a larger value of $\alpha_{\rm CE}\lambda$, more double WD systems would be produced (see Fig. 1). Note that Ablimit et al. (2016) also demonstrated that the Galactic SN Ia rate is in the range of $8.2\times10^{-5}\,\mathrm{yr}^{-1}$ to $1.7\times10^{-4}\,\mathrm{yr}^{-1}$ based on the violent merger scenario, which is generally similar to results from the present work.

Figure 4 displays the DTDs of SNe Ia predicted by the violent merger scenario. Here, we adopt a starburst of $10^{10}\,M_\odot$ in stars. The delay times of SNe Ia from the violent merger scenario are in the range of $\sim 90\,\mathrm{Myr}$ to the Hubble timescale, which corresponds to SNe Ia with young, intermediate and old ages. For the cases of $\alpha_{\rm CE}\lambda =$ 1 and 2, the large end of $\log(t)$ is the real cut-off on the basis of our calculations. For the case of $\alpha_{\rm CE}\lambda = 3$, the large end is artificial because the time has already reached the Hubble time.

Note that the likelihood of forming double WDs with unit mass ratio is still under debate. García-Berro et al. (2016) argued that it is difficult to produce double WDs that have a unit mass ratio, and that this kind of double WD is rare. The present work provides a possible path for the formation of double WDs with unit mass ratio and speculates that the number of double WDs with unit mass ratio may be not negligible, which is consistent with the results of Santander-García et al. (2015) and Ablimit et al. (2016).

For the CE ejection parameters, previous studies on the DD model of SNe Ia usually assumed that the values of $\alpha_{\rm CE}\lambda$ range from about 0.5 to 2.0 (e.g., Yungelson & Kuranov 2017; Liu et al. 2018). However, a larger CE ejection parameter is also widely used. Nelemans et al. (2000) studied the formation of double He WDs and they found the CE parameter $\alpha_{\rm CE}\lambda$ could be in the range of 1 to 3. Some observations targeting post CE binaries show that the values of $\alpha_{\rm CE}\lambda$ may vary from 0.01 to 5 (e.g., Zorotovic et al. 2010). In this work, we found that in order to reproduce the current stage of the planetary nebula Henize 2–428, a large CE ejection parameter of $\alpha_{\rm CE}\lambda = 3$ is needed.

4 SUMMARY

In the present work, we reproduce the evolutionary history and predict the future of the planetary nebula Henize 2–428. We found that this planetary nebula may originate from a primordial binary that has a $\sim 5.4\,M_\odot$ primary and a $\sim 2.7\,M_\odot$ secondary with an initial orbital period of $\sim 15.9\,\mathrm{d}$. After the double CO WD system is born, it would merge and produce an SN Ia through the violent merger scenario after about $\sim 840\,\mathrm{Myr}$. In order to form Henize 2–428, a large CE parameter ($\alpha_{\rm CE}\lambda = 3$) is needed. According to our calculations, we also found that the Galactic rate of SNe Ia is in the range $0.4 - 2.9\times10^{-4}\,\mathrm{yr}^{-1}$ and the delay times range from $\sim 90\,\mathrm{Myr}$ to the Hubble timescale. For a better understanding of the violent merger scenario of SNe Ia, more numerical simulations and more candidates for double WDs identified in observations are required.

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