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

Dong-Hao Wu, Dong-Dong Liu and Bo Wang

Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, China; wdh@ynao.ac.cn, liudongdong@ynao.ac.cn, wangbo@ynao.ac.cn

Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650216, China

University of Chinese Academy of Sciences, Beijing 100049, China

Center for Astronomical Mega-Science, Chinese Academy of Sciences, Beijing 100101, China

Received 2018 August 23; accepted 2018 October 31

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 $\sim 1$ and an orbital period of $\sim 4.2\, h$, 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 $\sim 15.9\, d$. 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 $\sim 840\, \text{Myr}$ 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 $2.9 \times 10^{-4}\, \text{yr}^{-1}$, and that the delay time is in the range of $\sim 90\, \text{Myr}$ 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., Podsiajowski 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...
Ia is the critical minimum mass of each WD for producing SNe Ia. A large sample of double CO WDs and found that the dynamical properties of SN 2011fe. Sato et al. (2016) simulated a violent merger scenario. Röpke et al. (2012) found that the violent mergers of two 0.9 $M_\odot$ 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 may be 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 $\sim 1.4 \pm 0.4$ 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 $\sim 4.2$ 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 ($q = M_{WD2}/M_{WD1}$) should be larger than 0.8, where $M_{WD1}$ is the mass of the more-massive WD, and $M_{WD2}$ 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., $t = t_{\text{evol}} + t_{GW} \leq t_{\text{Hubble}}$, where $t_{\text{evol}}$ is the evolutionary timescale from primordial binaries to the formation of double CO WDs, and $t_{GW}$ is the timescale during which double WDs are brought together by gravitational wave radiation, written as

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

in which $t_{GW}$ is in the unit of years, $P$ is the orbital period of double WDs in hours, and $M_{WD1}$ and $M_{WD2}$ 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, $2 \times 10^7$ 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 ($5 \, M_\odot \, yr^{-1}$) 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

$$\alpha_{CE} \left( \frac{G M_{\text{don}}^i M_{\text{acc}}^f}{2a_i} - \frac{G M_{\text{don}}^i M_{\text{acc}}^i}{2a_i} \right)$$

$$\alpha_{CE} = \frac{G M_{\text{don}}^i M_{\text{env}}}{\lambda R_{\text{don}}},$$

(2)

in which $G$, $M_{\text{don}}$, $M_{\text{acc}}$, $a$, $M_{\text{env}}$ and $R_{\text{don}}$ 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 ($\alpha_{CE}$) and a stellar structure parameter ($\lambda$). These two parameters may change with the evolutionary process (e.g., Ablimit et al. 2016). It has been suggested that the value of $\alpha_{CE}$ may vary with WD mass, secondary mass, mass ratio or orbital period (e.g., De Marco et al. 2011; Davis et al. 2012). Meanwhile, the values of $\lambda$ 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 $\alpha_{CE}$ and $\lambda$ 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. $\alpha_{CE}\lambda$) based on Equation (2), and assume $\alpha_{CE}\lambda = 1$, 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 in the orbital period–secondary mass ($\log P_{\text{orb}} - M_{\text{WD2}}$) plane. Red triangles, green crosses and blue dots represent the simulated results with $\alpha_{CE}\lambda = 1, 2$ 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).
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 2.2 \( M_\odot \) secondary, with an initial orbital period of \( 18,772 \) d. The primordial primary evolved to a subgiant after about 85.47 Myr. The radius of the primary reaches 22.39 \( R_\odot \) and fills its Roche lobe at \( t = 85.67 \) Myr (Stage 2), resulting in a stable mass-transfer process. After about 0.5 Myr, the H-rich shell of the primordial primary is exhausted and the mass transfer stops. In this case, the primordial primary becomes a subgiant star with a radius of 7.18 \( M_\odot \) MS star (Stage 3). The orbital period at this stage is \( 162 \) d. At \( t = 111.82 \) Myr, the primordial primary becomes a He subgiant with a radius of 5.44 \( M_\odot \), 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 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 \( t = 129.06 \) 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 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 \( t = 140 \) 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 \( M_{WD1} = 0.88 \) \( M_\odot \) and \( M_{WD2} = 0.78 \) \( M_\odot \). During this process, the orbital period shrinks to 0.716 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 Myr, resulting in the production of an SN Ia via the violent merger scenario at about \( t = 977 \) 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 \( M_\odot \) yr\(^{-1}\). From
this figure, we can see that the Galactic rates of SNe Ia range from about 0.5 to 2.0 (e.g., Yungelson & Kuranzov 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 $\alpha_{\text{CE}}$ could be in the range of 1 to 3. Some observations targeting post CE binaries show that the values of $\alpha_{\text{CE}}$ 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 $\alpha_{\text{CE}} = 3$ 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 $\sim 51.9$ d. After the double CO WD system is born, it would merge and produce an SN Ia through the violent merger scenario after about $\sim 840$ Myr. In order to form Henize 2–428, a large CE parameter ($\alpha_{\text{CE}} = 3$) is needed. According to our calculations, we also found that the Galactic rate of SNe Ia is in the range $0.4 - 2.9 \times 10^{-4}$ yr$^{-1}$ and the delay times range from $\sim 90$ 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.

Acknowledgements We acknowledge useful comments and suggestions from the anonymous referee. We also acknowledge useful comments and suggestions from Zhanwen Han. We would like to thank Linying
References

Howell, D. A. 2011, Nature Communications, 2, 350
Liu, D., Wang, B., Ge, H., Chen, X., & Han, Z. 2017a, arXiv:1710.03965
Wang, B. 2018, RAA (Research in Astronomy and Astrophysics), 18, 049