



A Helium Nova [HP99]159: Past, Present and Future

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Abstract

Type Ia supernovae (SNe Ia) are among the most extreme phenomena in the Universe and play a crucial role in the studies of stellar evolution, galactic chemical evolution and cosmology. However, the progenitors of SNe Ia are still under debate. It has been suggested that SNe Ia could be produced by helium (He) novae in the single-degenerate channel. Recently, a He nova named [HP99]159 was proposed to be a progenitor candidate for SNe Ia, in which the white dwarf (WD) has a mass of $1.2^{+0.18}_{-0.4} M_{\odot}$, the He star's mass ranges from $0.8 M_{\odot}$ to $2.0 M_{\odot}$ and the orbital period was suggested to be 2.33 or 1.16 days. In the present work, we evolved a large number of primordial binaries to the formation of WD+He star systems and investigated their future evolution. We provided a representative evolutionary track of [HP99]159 and found that [HP99]159 may originate from a primordial binary with a $6.16 M_{\odot}$ primary and a $4.32 M_{\odot}$ secondary with an initial orbital period of 5110 days. We also found that [HP99]159 might evolve to an SN Ia explosion as suggested by previous studies, or it may also form an accretion-induced collapse event or a wide double WD. Further detailed observations are needed in future studies to provide more information about the precise nature of [HP99]159.

Key words: (stars:) binaries (including multiple): close – stars: individual ([HP99]159) – stars: evolution – (stars:) supernovae: general – (stars:) white dwarfs

1. Introduction

Supernovae (SNe) are among the most extreme phenomena in the Universe. Type Ia SNe (SNe Ia) are characterized by strong Si II absorption lines and the absence of H and He lines near peak luminosity (Filippenko 1997). SNe Ia are widely utilized as standard candles for measuring cosmic distances due to their high luminosity and significant uniformity, leading to the discovery that the Universe's expansion is accelerating (Riess et al. 1998). SNe Ia are widely regarded as the result of thermonuclear explosions of carbon-oxygen white dwarfs (CO WDs) in close binary systems (e.g., Hoyle & Fowler 1960; Nomoto et al. 1984). However, the progenitor systems and explosion mechanisms of SNe Ia remain incompletely understood, which could affect the accuracy of measuring cosmological distances (e.g., Wang & Han 2012; Maoz et al. 2014; Wang 2018). To date, various progenitor models have been proposed for SNe Ia, with the single-degenerate (SD) model and double-degenerate (DD) scenario models being among the most extensively studied and widely accepted.

In the SD model, a CO WD accumulates material from a non-degenerate companion star, which could be a main sequence (MS) star, a red giant, a He star or even an asymptotic giant branch (AGB) star (e.g., Li & Van Den Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004;

Chen & Li 2007; Liu et al. 2010, 2019; Wang & Han 2010a; Li et al. 2023). The accreted material burns on the WD surface, and the WD may increase its mass to the Chandrasekhar mass limit (M_{Ch}), leading to the production of an SN Ia. The explosion of the WDs with M_{Ch} in the SD model can well reproduce spectroscopy and the observed light curves of most SNe Ia (Wang & Han 2012). In the DD model, driven by gravitational wave radiation a CO WD merges with another CO WD, and if the total mass of the two CO WDs is greater than M_{Ch} , then an SN Ia will be produced (e.g., Iben & Tutukov 1984; Han 1998; Liu et al. 2017). The birth rates and delay time distribution of SNe Ia can be well reproduced by the DD model (Liu et al. 2018).

A classical nova is thought to be a runaway thermonuclear event that occurs on a WD accreting H-rich material from its companion star in a close binary (Sparks et al. 1978). Kato et al. (1989) predicted that He novae are a subclass of classical novae, which are nova outbursts caused by He shell flashes on the WDs surface. They proposed two kinds of He accretion: a WD accreting He-rich material from a He companion star, and a WD accreting H-rich material and burning into He then accumulating onto its surface. The mass loss in He novae during their outburst is suggested to be weaker than that in classical H novae, and most of the accreted He burns into carbon and oxygen, accumulating on the surface of the WD (e.g., Kato & Hachisu 1999, 2004). Therefore, He-accreting

massive WDs could be the progenitors of SNe Ia (e.g., Wang et al. 2017; Qi et al. 2022).

[HP99]159 is an X-ray source located in the Large Magellanic Cloud, which was detected in the early 1990s by ROSAT and XMM-Newton (Haberl & Pietsch 1999). Recently, Greiner et al. (2023) reported that [HP99]159 has a very soft X-ray spectrum with an effective blackbody temperature of $kT = 42\text{--}44\text{ eV}$ by using ROSITA observational data. They obtained its optical spectra between 2020 August and October, showing no sign of H lines, which suggests that the binary system [HP99]159 consists of an X-ray emitting WD and a He companion. They also suggested that in [HP99]159 the WD has a mass of $1.2^{+0.18}_{-0.4} M_{\odot}$ and the He star has mass errors ranging from $0.8 M_{\odot}$ to $2.0 M_{\odot}$. A Lomb–Scargle periodogram showed that there are two uncertain orbital periods, and the longer-period folded light curve indicates that it has a lower variance and a significant odd–even asymmetry, thus leading to the possible orbital periods of 2.33 or 1.16 days.

In this work, we will provide a representative evolutionary track of the supersoft X-ray source [HP99]159 by evolving 10^8 primordial binary systems into CO/ONe WD+He star systems, and explore their possible outcomes. In Section 2, we introduce the numerical methods and fundamental assumptions adopted in this work. Section 3 presents the corresponding results and discussion, followed by a summary in Section 4.

2. Numerical Methods

2.1. Stellar Evolution Code

Employing version 12778 of the stellar evolution code MESA (see Paxton et al. 2010, 2019), we simulate the evolution of WD+He star systems within the observational parameters of [HP99]159. In this work, the WDs are treated as point masses, and detailed methods and fundamental assumptions are similar to those of Liu & Wang (2023). In order to explore the outcomes of [HP99]159, we investigate the evolution of WD+He star systems that satisfy the following conditions:

1. Greiner et al. (2023) suggested that the WD in [HP99]159 has a mass of $1.2^{+0.18}_{-0.4} M_{\odot}$. Kato et al. (2023) presented a Hertzsprung–Russell (HR) diagram depicting the evolutionary tracks of WDs with varying masses in He nova systems, comparing these tracks to the observational error box of [HP99]159. They found that the WD out of the range of $1.2 M_{\odot}\text{--}1.35 M_{\odot}$ could be excluded. In our MESA simulations, we investigated the evolution of WDs with $1.15 M_{\odot}$ and $1.2 M_{\odot}$, as the WDs can grow in mass during the evolution of He novae. The results for WDs with $1.2 M_{\odot}$ will be used to generate the

initial parameter space for accretion to the Chandrasekhar mass limit.

2. In this work, we suppose that the He stars have masses ranging from $0.8 M_{\odot}$ to $2.0 M_{\odot}$. There are two uncertain orbital periods P_{orb} of 1.16 or 2.32 days, so we artificially assume the two possible orbital period as upper and lower limits in the simulation process.
3. The mass accretion process is crucial for binary evolution and accretion physics. Given the luminosity of $1800 L_{\odot}$ for [HP99]159, the accretion rate should be below the He layer flash critical rate with $10^{-5.93} M_{\odot} \text{ yr}^{-1}$ for a $1.2 M_{\odot}$ WD (Kato & Hachisu 2004). However, excessively low accretion rate for He novae would result in rapid luminosity variations and long recurrence periods, which is inconsistent with the observed stability of [HP99]159. We thus follow Kato et al. (2023), adopting a minimum accretion rate of $6 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ to reconcile luminosity variations.

2.2. BPS Approaches

Utilizing the rapid evolution code (Hurley et al. 2002), we performed a series of Monte Carlo binary population synthesis (BPS) simulations to investigate the evolution from primordial binaries to CO/ONe WD+He star systems. In these systems, the He stars fill their Roche lobe at the He MS or He subgiant stage and transfer He-rich material onto the WDs. We evolve 10^8 primordial binaries in this simulation, and assume that WDs with masses in the range of $0.8 M_{\odot}\text{--}1.3 M_{\odot}$ could evolve into the observation range of [HP99]159, detailed discussion is provided in Section 3.1. Finally, we obtain the distribution of CO/ONe WD+He star binaries and present a representative evolutionary path of [HP99]159. Some of the underlying assumptions and initial parameter settings are as follows:

1. We assume that all stars are binaries with circular orbits.
2. The initial mass function of the primordial primaries is described using the prescription of Miller & Scalo (1979).
3. The initial mass ratio ($q = M_2/M_1$) is taken to be a constant distribution, i.e., $n(q) = 1$.
4. We adopted a solar metallicity of $Z = 0.02$ in our simulation.
5. For the orbital separations, we assume a constant $\log a$ distribution for wide binaries and a smoothly decreasing case for close binaries (Han et al. 1995).

The evolution of the common envelope (CE) plays a significant role in the formation and evolution of CO WD +He star binaries. However, the CE ejection process is still not defined (Ivanova et al. 2013). It is common for the relationship between the orbital energy and the binding energy to be used to parameterize the CE interaction. Our investigation adopts the standard energy prescription to study the outcomes of the

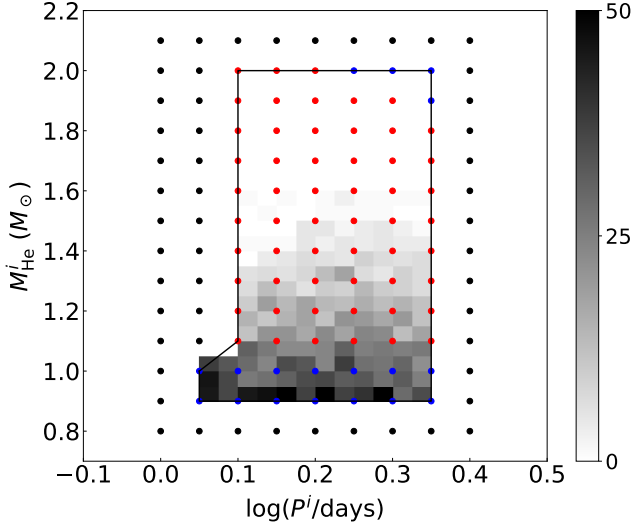


Figure 1. Possible outcomes and probability distribution of $1.2 M_{\odot}$ CO WD + He binaries in the initial orbital period and initial He star mass panel. The gradient of gray shading represents the population density of primordial binaries that evolve into CO WD + He star systems and falling within this parameter space. The red dots indicate CO WD + He star systems that can accrete He-rich material reaching the M_{Ch} and produce SNe Ia, and the blue points indicate that these systems will evolve to wide double WDs.

CE phase (Webbink 1984). In addition, the prescription involves two uncertain parameters: the CE ejection efficiency (α_{CE}) and the stellar structure parameter (λ). In our model, λ is set to 0.5, and α_{CE} is set to 3.0.

3. Results and Discussion

3.1. Probability Distribution and Outcomes of CO WD + He Star Systems

Figure 1 presents the possible outcomes of $1.2 M_{\odot}$ CO WD + He star binaries and the corresponding probability distribution within the range of observed parameters, where M_{He}^i represents the He star's initial mass and P^i represents the initial orbital period of the binary systems. In this figure, the gradient of gray shading represents the population density of primordial binaries that can evolve into CO WD + He star systems based on our BPS study. Each point represents a CO WD + He star system in our simulation, where the red points represent CO WD + He star systems in which the CO WDs can eventually reach the M_{Ch} by accreting He-rich material and producing SNe Ia, and the blue points indicate that the systems will eventually form wide double CO WDs. If the initial parameters of the binary system lie within our parameter space, the system's evolutionary path would include a phase corresponding the current state of [HP99]159.

We simulate the evolution of 10^8 primordial binaries by using the BPS method. We find that a total of 2329 CO WD + He star systems could evolve to the current observational error of [HP99]159. These systems have initial orbital periods

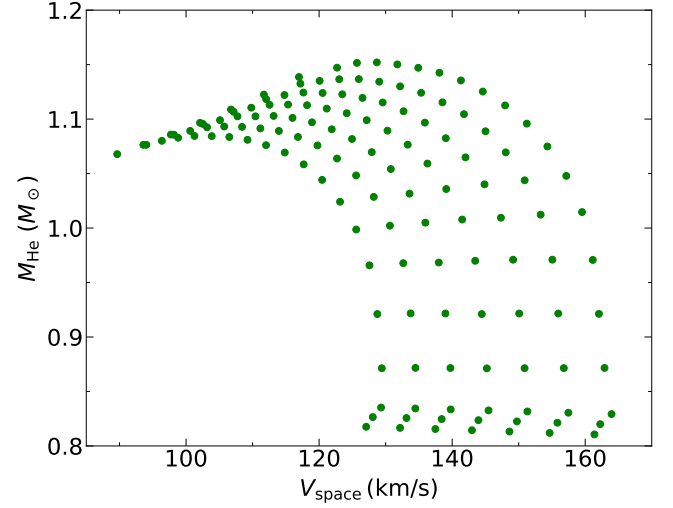


Figure 2. Space velocity distribution of the He stars after the SN explosion.

ranging from 1.16 to 2.33 days and He star masses ranging from $0.9 M_{\odot}$ to $2.0 M_{\odot}$, and all of the CO WDs have an initial mass less than $1.2 M_{\odot}$. We note that CO WD + He star systems are mainly concentrated in the low He mass region. About 50% of them are located in the red region, suggesting that up to 50% of these WDs can accrete He-rich material and eventually reach the M_{Ch} , potentially triggering an SN Ia explosion via the SD model. The others will evolve into double CO WD systems, which are not expected to produce SNe Ia due to their long merging timescale, which exceeds the Hubble timescale (see also Liu et al. 2018).

Observational data and previous studies indicated that the current mass of the WD in [HP99]159 is between $1.2 M_{\odot}$ and $1.35 M_{\odot}$. The initial parameter space illustrated in Figure 1 is derived from the evolutionary process of $1.2 M_{\odot}$ WDs. In our BPS approach, we limited the initial mass of WDs to a range of $0.8 M_{\odot}$ – $1.3 M_{\odot}$. Imposing a mass limit on WDs would not affect the variety of outcomes, but influences the parameter distribution and the probability of producing SNe Ia. Wang et al. (2009) suggested that the WDs with less initial masses possess a smaller parameter space for producing SNe Ia. If the initial mass of the WD is $1.1 M_{\odot}$, the probability of producing an SN Ia would be smaller than the results we have given. However, if the initial WD mass is less than or equal to $1.0 M_{\odot}$, [HP99]159 will eventually form a wide double CO WD.

In the SD model, the companion may survive and show identifiable properties after SN Ia explosion. It probably has a high space velocity and becomes a runaway star moving away from the SN remnant (e.g., Han 2008; Wang & Han 2010b). For a binary star system with an orbital period of several days, the effect of the SN Ia explosion on the companion star's velocity is very weak, and its post-explosion space velocity is primarily determined by its pre-explosion orbital velocity (Liu

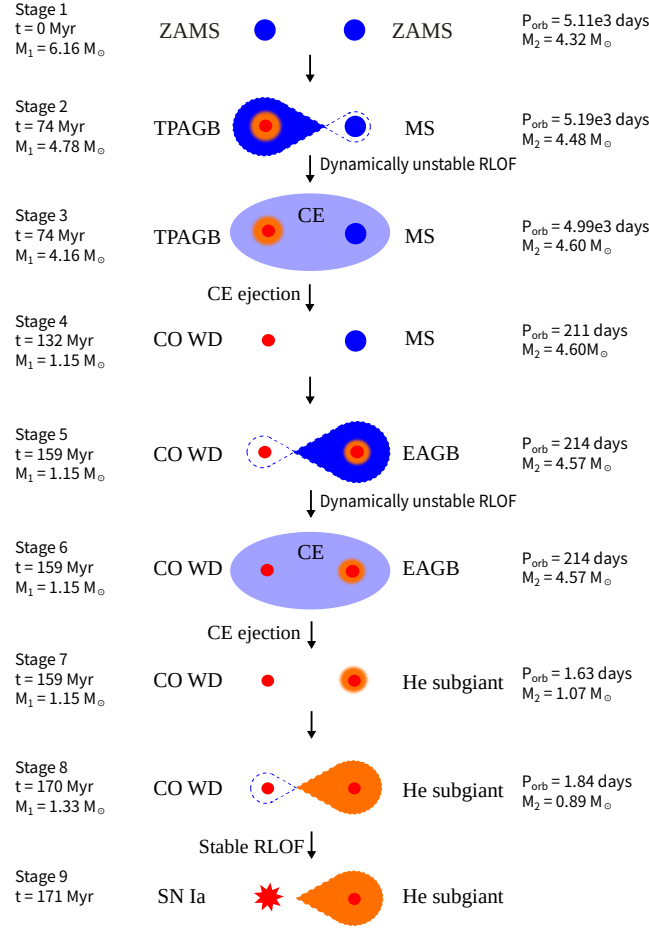


Figure 3. A representative evolutionary track and future evolution of [HP99]159.

et al. 2013). In this work, we ignore the effect of the SN Ia explosion and assume that the space velocity of the companion is similar to the orbital velocity. In Figure 2, we present the space velocity of these binaries at the moment of SN explosion. We can see that the surviving companions have space velocities between ~ 90 and $\sim 165 \text{ km s}^{-1}$. The space velocities of these companions exceed the typical runaway star velocity criterion of around $30\text{--}40 \text{ km s}^{-1}$, which are high enough to potentially escape the gravity of the host galaxy (Guo et al. 2024). Therefore, a binary system similar to [HP99]159 may leave behind a runaway star after an SN Ia explosion.

3.2. A Representative Evolutionary Track and Future Evolution of [HP99]159

Figure 3 shows a representative evolutionary track of [HP99]159. The primordial binary system initially comprises two zero-age main sequence (ZAMS) stars, the orbital period of the binary is about 5110 days with a primary star mass of $6.16 M_{\odot}$ and a secondary star mass of $4.32 M_{\odot}$ (Stage 1). After approximately 74 Myr, the primary star evolves into the

thermally pulsing AGB stage, fills its Roche lobe and transfers material to the secondary (Stage 2). Dynamical instability during Roche lobe overflow (RLOF) triggers the formation of CE evolution (Stage 3). Following CE expulsion, the primary star evolves into a CO WD of $1.15 M_{\odot}$, while the secondary star maintains its MS stage with a mass of $4.60 M_{\odot}$, and the orbital period reduces to 211 days (Stage 4). The primordial secondary star subsequently reaches the early AGB stage and eventually fills its Roche lobe at $t \approx 159 \text{ Myr}$ (Stage 5). At this stage, the mass transfer process is also dynamically unstable, resulting in a second CE formation (Stage 6). After the second CE ejection, we obtain a binary system consisting of a $1.15 M_{\odot}$ CO WD and a $1.07 M_{\odot}$ He subgiant with an orbital period of 1.63 days (Stage 7).

After the formation of the CO WD+He star systems, we simulated the subsequent evolution of these systems in MESA. Figures 4 and 5 illustrate the evolutionary track corresponding to Stages 7–9 in Figure 3. During this period, the He star gradually fills its Roche lobe and begins to transfer He-rich material to the WD. As the accreted He accumulates on the surface of the WD, its temperature and luminosity gradually

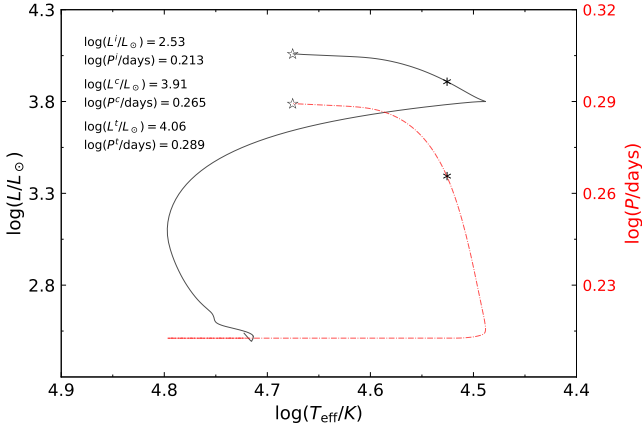


Figure 4. Evolutionary track of the binary from Stages 7 to 9 in Figure 3. The solid line illustrates the HR diagram, while the red dash-dotted line shows how the orbital period changes with effective temperature. The pentagrams are used to indicate the points where an SN Ia is produced. The asterisks represent the current state of [HP99]159.

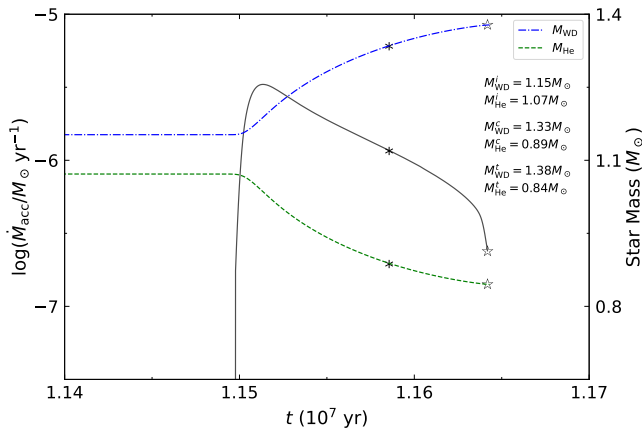


Figure 5. Mass accretion process from Stages 7 to 9 in Figure 3. The solid line represents the accretion rate of the WD, and the blue and green lines show how the masses of the WD and He star change with time, respectively.

increase until thermonuclear reactions become uncontrollable, triggering a He nova outburst. Due to the mass loss caused by the optically thick wind, the accretion rate of WD begins to decline. After the wind ceases, the He nova enters the decay phase, and the WD photosphere emits supersoft X-rays and gradually accumulates mass at a low accretion rate. At $t \approx 170$ Myr, the system matches the current observational error range (Stage 8). Finally, after 6×10^4 yr, the CO WD reaches the M_{Ch} and triggers an SN Ia explosion.

Observations revealed that the absolute V -band magnitude of [HP99]159 is $M_V = -2.8$ mag. Based on the Mesa simulation, the effective temperature of the He star is approximately 33,000 K. According to the Planck equation, the numerical integration in the V -band shows the He star has a luminosity of $2.16 \times 10^{35} \text{ erg s}^{-1}$. In addition, the luminosity

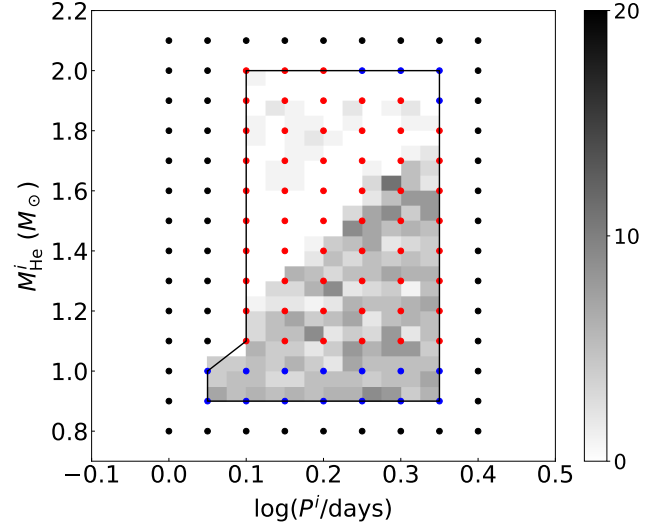


Figure 6. Similar to Figure 1, but this figure shows the outcomes and probability distribution of primordial binary systems within the parameter space as they evolve into ONe WD and He star systems.

of the He star is obviously smaller than that of the accretion disk (Greiner et al. 2023). Therefore, the total luminosity of Stage 8 in Figure 3 should be greater than $4.32 \times 10^{35} \text{ erg s}^{-1}$, which corresponds to an absolute V -band magnitude of $M_V = -2.74$ mag.

3.3. CO WD or ONe WD

WDs are generally categorized based on their elemental composition into He WD, CO WD, and ONe WD (e.g., Han et al. 1994; Zhang et al. 2024). For the WD in the mass range from $0.8 M_{\odot}$ to M_{Ch} in [HP99]159, it is also possible to be an ONe WD. In this study, the WD is treated as a point mass. Thus the initial parameter space for the WD mass growth process, which is calculated by MESA and shown in Figure 1, is applicable to both CO WDs and ONe WDs. In contrast to a CO WD, a massive ONe WD in a close binary system may form a neutron star through an accretion-induced collapse (AIC) process when its mass approaches M_{Ch} (Moriya 2016). Therefore, we have discussed the scenario if the WD in [HP99] 159 is an ONe WD, and the relevant results have been shown in Figure 6.

In our BPS simulation, a total of 649 ONe WD+He star systems were located in the observed error of [HP99]159 after the evolution of 10^8 primordial binaries, with about 70% of them located in the red region. In contrast to the systems shown in Figure 1, the selected ONe WD+He star systems in the parameter space exhibit a much broader range of He mass, and mainly over longer orbital periods. Among these systems we evolved, approximately 75% of them have initial masses greater than $1.2 M_{\odot}$. This suggests that the actual probability of an AIC process forming is higher than 70% which is

indicated by the gray shaded distribution in Figure 6. The remaining systems cannot undergo an AIC event and eventually evolve to the ONe WD+CO WD systems (Liu & Wang 2020).

4. Summary

By combining the results of detailed binary evolution and BPS approach, we provided the possible outcomes of CO/ONe WD+He star systems and the corresponding probability distributions within the observational errors of [HP99]159. We found that [HP99]159 appears to have originated from a primordial binary star consisting of a $6.16 M_{\odot}$ primary and a $4.32 M_{\odot}$ secondary with an orbital period of 5110 days. [HP99]159 was formed after undergoing two CE ejections and following RLOF. If the WD in [HP99]159 is a CO WD, it will evolve to an SN Ia with the probability of less than 50%, implying that it is more likely to form a wide double CO WD. In the case of ONe WD, there is over a 75% probability that an AIC event will occur, leaving little probability of forming an ONe WD+CO WD system. In order to determine the outcome of [HP99]159, more analytical methods and further precise observations are required in the future to reveal its nature.

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