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Possible Formation Scenarios of ZTF J153932.16+502738.8—A Gravitational Source Close to the Peak of *LISA*'s Sensitivity

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Abstract

ZTF J153932.16+502738.8 (ZTFJ1539) is an eclipsing double-white-dwarf system with an orbital period of 6.91 minutes, and a significant source for *LISA* detection of gravitational waves. However, the massive white dwarf (WD), with a mass of about 0.61 $M_\odot$, has a high effective temperature (48,900 K), and the lower-mass WD, with a mass of about 0.21 $M_\odot$, has a low effective temperature (<10,000 K). This discrepancy challenges the popular theory of binary evolution. We investigate the formation of ZTFJ1539 via nova and Algol scenarios. Assuming that the massive WD in ZTFJ1539 just experiences a thermonuclear runaway, the nova scenario can explain the effective temperatures of the two WDs in ZTFJ1539. However, in order to enlarge a semi-detached orbit of about 4–5 minutes to a detached orbit of about 7 minutes, the nova scenario needs a much higher kick velocity of about 200 km s^{-1} during nova eruption. The high kick velocity can result in a high eccentricity of about 0.2–0.6. The Algol scenario can also produce ZTFJ1539 if we take a high efficient parameter for ejecting the common envelope and enhance the mass-loss rate via stellar wind trigger by tidal effect.

Unified Astronomy Thesaurus concepts: Close binary stars (254); White dwarf stars (1799); Classical novae (251)

1. Introduction

Gravitational radiation can be produced by binaries with short orbital periods. The LIGO/Virgo detectors have successfully observed the gravitational waves (GWs) emitted in the kHz regime by several mergers of double black holes and a merger of double neutron stars (Abbott et al. 2016, 2017, 2018). In fact, comparing with double black holes and neutron stars, double-white dwarfs (DWDs) are predominant (Nelemans et al. 2001a). In the Milky Way, Nelemans et al. (2001b) estimated that there are about 10^7 DWDs emitting GWs in the MHz band. These GWs can be detected by the *Laser Interferometer Space Antenna* (*LISA*), which can observe GWs with a band of about 0.1 and 1000 mHz (Amaro-Seoane et al. 2017). Cornish & Robson (2017) estimated that *LISA* can find about 10^4 DWDs.

Recently, based on the updated distances from *Gaia* Data Release 2, Kupfer et al. (2018) provided 13 binary systems that can emit GWs strong enough to be detectable by *LISA*. Very recently, Burdge et al. (2019) observed an eclipsing DWD ZTF J153932.16+502738.8 (ZTFJ1539) with an orbital period of 6.91 minutes, which is the shortest in detached DWDs. The GW emitted by this DWD is closed to the most sensitive *LISA* band, and *LISA* can detect it within a week (Burdge et al. 2019). Therefore, ZTFJ1539 is a significant source for *LISA* detection of GWs (Littenberg & Cornish 2019).

For binary evolution theory, this scenario is very interesting. The primary and secondary WDs have masses of about 0.61 and 0.21 $M_\odot$ (Burdge et al. 2019), respectively. In this paper, the WD with larger mass is called the primary WD, while the other is called the secondary WD. Usually, in DWDs the primary WD forms first and its cooling timescale is shorter than that of the secondary WD. Surprisingly, the effective temperature of the primary WD is about 48,900 ± 900 K, which is higher than the temperature (<10,000 K) of the secondary WD (Burdge et al. 2019). Burdge et al. (2019) gave two possible explanations. One is tidal heating. Due to an extremely short orbital period, tidal distortion dissipates the tidal energy in the WD, which results in heating and spinning up the WD (Fuller & Lai 2013). Another is recent accretion, which results in a nova eruption. Having considered that the temperature of WD heated by the tidal distortion through more realistic calculations is close to 25,000 K, Burdge et al. (2019) suggested the latter scenario is more likely.

Theoretically, in DWDs the accretion should occur in semi-detached systems, and result in X-ray emission. However, ZTFJ1539 is a detached system and has no detectable X-ray emission (Burdge et al. 2019). Therefore, there should be a mechanism for a transition from a semi-detached system to detached system if ZTFJ1539 undergoes a nova eruption. In addition, it is possible that the secondary WD may form earlier than the primary WD if the binary experiences mass transfer to become an Algol system (e.g., Dervişoğlu et al. 2010; van Rensbergen et al. 2011).

In this paper, we investigate the possibility that ZTFJ1539 was produced by a nova eruption with a kick velocity or an Algol system. In Section 2, we simulate the nova eruptions in DWDs, and discuss the possibility of ZTFJ1539 forming via a nova scenario. How the Algol scenario might have produced ZTFJ1539 is discussed in Section 3. The main conclusions appear in Section 4.

2. Nova Scenario

Nova eruptions usually appear in binary systems in which a thermal nuclear runaway occurs on the surface of a WD accreting material from its companion. In general, most companions in nova binaries are normal stars (main sequence or giant stars), while about 60 nova binaries have hydrogen-deficient companions (e.g., Gallagher & Starrfield 1978; Belczyński et al. 2000; Lü et al. 2006; Ramsay et al. 2018). The former are called cataclysmic variables (CVs), and the latter are called ultra-compact cataclysmic variables (AM CVn). However, ZTFJ1539 is a DWD binary.

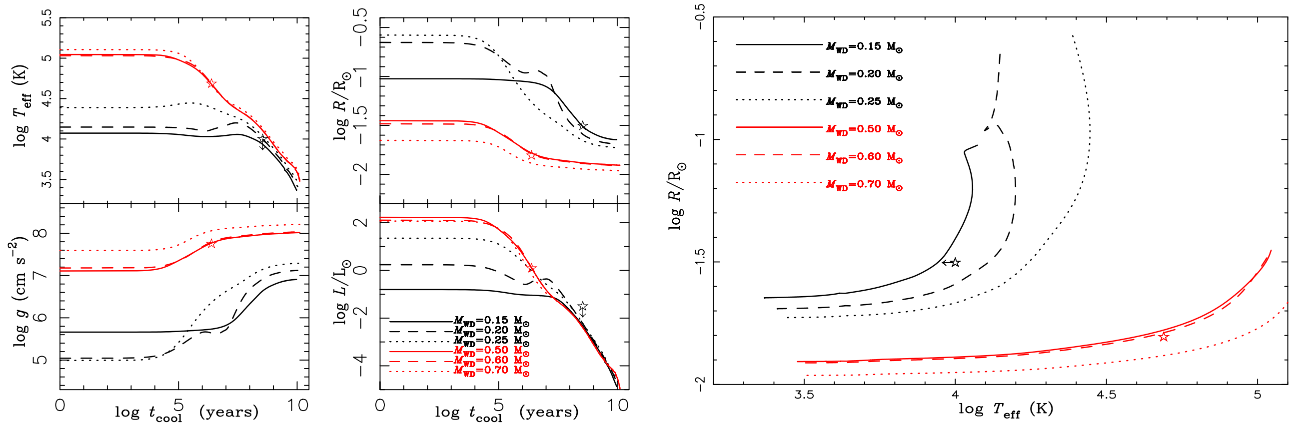

Figure 1. The evolutions of the effective temperature, radius, acceleration gravity, and luminosity during WD cooling phase are given in the left panels. The effective temperature versus the radius is shown in the right panel. The black and red lines represent He and CO WDs, respectively. The line styles represent WDs with different masses. The black and red stars give the positions of He and CO WDs in ZTFJ1539. The observational data come from Burdge et al. (2019).

It is composed of a CO WD with mass of about 0.61 $M_\odot$ and a He WD with mass of about 0.21 $M_\odot$ (Burdge et al. 2019). If the He WD fills its Roche lobe, mass transfer occurs. Marsh et al. (2004) investigated the stability of mass transfer between DWDs. If mass transfer is stable, ZTFJ1539 will undergo a nova eruption, and evolve into an AM CVn (Burdge et al. 2019). If the transfer is not stable, it could evolve into R Coronae Borealis Stars (e.g., Han 1998; Clayton 2012). In order to simulate the nova eruption in ZTFJ1539, we must construct models of He and CO WD.

2.1. Nova Model

Modules for Experiments in Stellar Evolution (MESA, [rev. 11108]; Paxton et al. 2011, 2013, 2015, 2018) offers a test_suite for producing He WD and CO WD. Using MESA, we create CO WDs with masses of 0.5, 0.6, and 0.7 $M_\odot$, and He WDs with masses of 0.15, 0.20, and 0.25 $M_\odot$, respectively. Figure 1 shows the evolutions of the effective temperature, radius, gravity acceleration, and luminosity during the WD cooling phase. The cooling age of a nascent WD with a mass of 0.6 or 0.2 $M_\odot$, which evolves to the state of the primary or the secondary in ZTFJ1539, is respectively about 2.4 M or 300 M years, which is consistent with the estimate of Burdge et al. (2019). Based on Figure 1, the primary or the secondary can be covered by a single-star model. However, ZTFJ1539 is a DWD. According to popular binary theory, a WD with mass higher in DWD should be cooler because it is older and its cooling timescale is shorter. Burdge et al. (2019) considered that the primary in ZTFJ1539 just experienced a nova eruption. Its primary and secondary are CO WD and He WD, respectively. This means that the nova is triggered by the helium-rich material accreted by the primary from the secondary. Very recently, using the FUN evolutionary code combined with a large nuclear network, Piersanti et al. (2019) simulated the nova eruptions produced by helium-accreting WDs in AM CVn stars.

In this work, following Denissenkov et al. (2013, 2014) and Zhu et al. (2019), we use test_suit case nova in MESA to simulate nova eruption in ZTFJ1539. Based on the observations of Keck I, Burdge et al. (2019) found that narrower hydrogen emission lines apparently come from the cooler secondary, and the irradiated surface of the secondary had some weak neutral helium emission lines. It is difficult to determine the chemical compositions of the secondary. In our model, we simulate nova eruptions triggered by hydrogen-rich or hydrogen-deficient accreted materials. The chemical compositions of the former are $X(\mathrm{H}) = 0.7$, $X(\mathrm{He}) = 0.28$, and $Z = 0.02$, while those for the latter are $X(\mathrm{H}) = 0.0$, $X(\mathrm{He}) = 0.98$, and $Z = 0.02$. The abundances of metal elements are similar to those of the Sun.

2.2. Discussions

Figure 2 gives the evolutions of the effective temperatures, the radii, the gravitational acceleration, and the luminosities for WDs after novae reach the maximum luminosity. The hydrogen-rich and hydrogen-deficient models give similar results. The primary of ZTFJ1539 can be explained as a WD that experienced a nova eruption about 8000 yr ago. Compared with the radius and the gravitational acceleration of the primary, the model of WD with 0.5 $M_\odot$ mass is better. However, both of them greatly depend on the hydrogen mass around the WD surface. In our simulation, we consider the mass loss when the luminosity of the nova exceeds the Eddington luminosity, and may underestimate the hydrogen mass. In addition, they also depend on the WD cooling, which is also affected by the convection, the radiative transfer, crystallization, and so on (Wood 1992; Hansen 1999; Liu & Lü 2019).

Usually, the novae in DWDs occur in semi-detached systems. However, ZTFJ1539 is a detached binary. Burdge et al. (2019) considered that the orbit was widened because an amount of mass ($10^{-4} M_\odot$) was ejected during the nova eruption. In order to discuss these effects, considering that the nova eruption may be aspherically symmetric and following the methods for investigating the kick velocity of a supernova in Brandt & Podsiadlowski (1995) and Hurley et al. (2002), we assume that the WD also receives a kick velocity when it ejects an amount of mass. The kick velocity v_k abides by a Maxwellian distribution

$$P(v_\mathrm{k}) = \sqrt{\frac{2}{\pi}}\frac{v_\mathrm{k}^2}{\sigma_\mathrm{k}^3}e^{-v_\mathrm{k}^2/2\sigma_\mathrm{k}^2}. \quad (1)$$

In this work, σ_k is taken as 50 and 200 km s^{-1}, respectively.

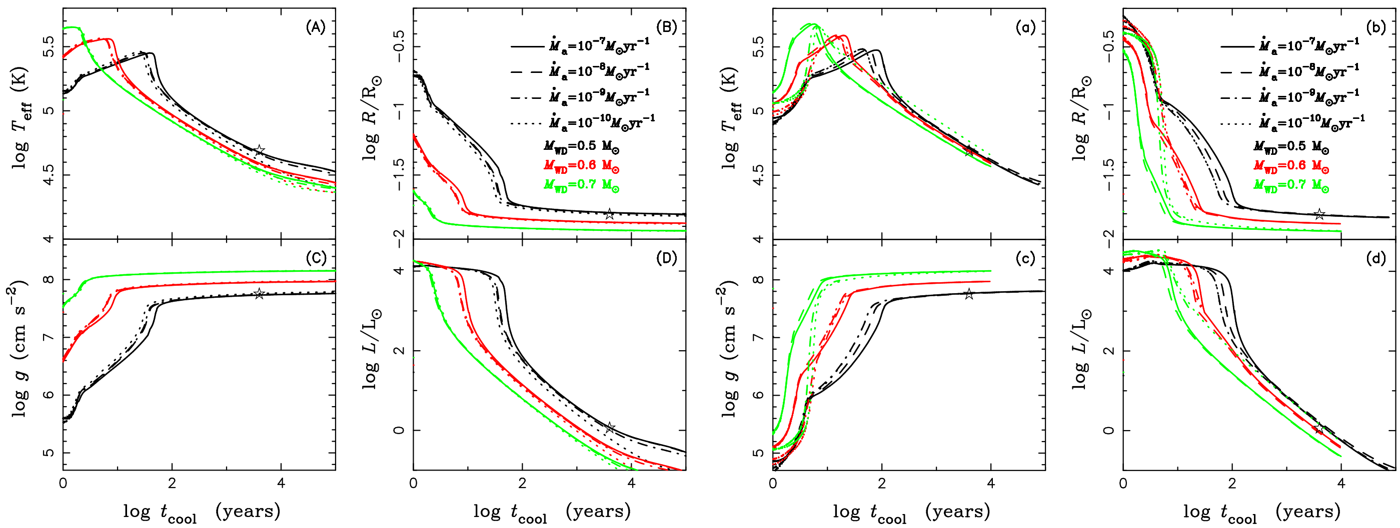

Figure 2. Evolutions of the effective temperature, radius, gravitational acceleration, and luminosity after novae reach the maximum luminosity. The left four panels noted by (A), (B), (C), and (D) are for nova eruptions triggered by hydrogen-rich accreted materials, and the right four panels noted by (a), (b), (c), and (d) are for hydrogen-deficient accreted materials, respectively. The black, red, and green lines represent the nova models with CO WD's masses of 0.5, 0.6, and 0.7 $M_\odot$, respectively. The solid, dashed, dotted–dashed, and dotted lines represent the nova models with mass-accretion rates of 10^{-7}, 10^{-8}, 10^{-9}, and 10^{-10} $M_\odot$ yr^{-1}, respectively. The black star gives the observational value of the primary in ZTFJ1539 (Burdge et al. 2019).

Using a synthesis population method, we construct a sample of 10^7 binary systems (details can be seen in Lü et al. 2011, 2012, 2013; Zhu et al. 2013, 2015). The initial mass function comes from Miller & Scalo (1979), a constant mass-ratio distribution is considered (Mazeh et al. 1992), and the distribution of separations is taken as

$$\log a = 5X + 1, \tag{2}$$

where X is a random variable uniformly distributed in the range [0,1] and a is in $R_\odot$.

Using the rapid binary star evolution (BSE) code (Hurley et al. 2002), we obtain about 3.4×10^5 CO + He WDs from 10^7 binary systems. Figure 3(a) gives the distribution of the primary masses and the orbital periods for nascent CO + He WDs. Due to the gravitational release, the orbits of these systems shrink. Within Hubble times, about 44% of them evolve into semi-detached systems, as shown in Figure 3(b). Because the He WDs in our simulations have very thick hydrogen envelopes ($\sim 10^{-5} M_\odot$), their orbital periods are shorter than about 6 minutes when the He WDs fill their Roche lobes. If He WDs have very thick hydrogen envelopes, they can fill their Roche lobes at longer periods. When the WDs with higher mass in the semi-detached systems accrete the matter from their companions, nova eruptions occur. Burdge et al. (2019) found that the orbit of ZTFJ1539 only widened slightly if a mass of 10^{-4} $M_\odot$ was ejected during a nova eruption, and ZTFJ1539 would become a semi-detached system again about 100 yr after a nova eruption. However, as Figure 2 shows, the primary of ZTFJ1539 may have evolved for about 8000 yr after a nova eruption. In fact, based on the theoretical model, the mass ejected during a nova eruption is between about 10^{-3} and $10^{-8} M_\odot$(Yaron et al. 2005; Zhu et al. 2019). Compared with WD mass, the mass ejected is too small. It hardly results in a large orbital widening.

In our work, we consider the effects of kick velocity. However, as Figure 3(c) shows, kick velocities with $\sigma_k =$ 50 km s^{-1} cannot widen the orbits up to 6 minutes. When σ_k increases to 200 km s^{-1}, ZTFJ1539 can be covered by our simulation. Simultaneously, kick velocity can also result in an elliptical orbit. Figure 4 shows the distributions of eccentricities for $\sigma_k = 50$ and 200 km s^{-1}, respectively. Our results indicate that the eccentricity of ZTFJ1539 should be between about 0.2 and 0.6 if the orbit of ZTFJ1539 is broadened from about 5–6.91 minutes by a nova eruption. Usually, a binary system with high eccentricity undergoes a large degree of apsidal precession that would manifest itself in the eclipse timing residuals. However, Burdge et al. (2019) believed that the eccentricity of ZTFJ1539 should be zero because any sign of apsidal precession was not detected.

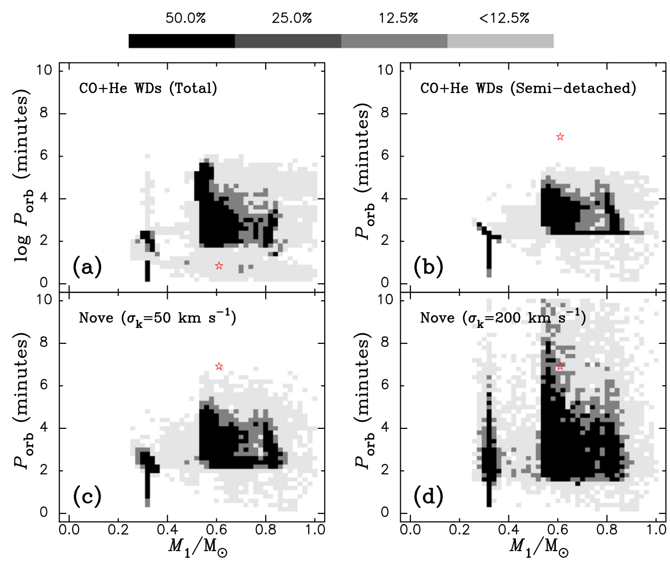

Figure 3. Primary masses versus orbital periods of CO + He WD systems. (a) Nascent CO + He WDs. (b) Semi-detached CO + He WDs. Panels (c) and (d) show the CO + He WDs after nova eruptions with kick velocities of $\sigma_k = 50$ and 200 km s^{-1}, respectively. The red star gives the position of ZTFJ1539.

In fact, Hobbs et al. (2005) analyzed the proper motion of 233 pulsars and suggested that σ_k of core-collapse supernovae (CCSNe) are about 265 km s^{-1}. In general, the energy released by CCSNe is 10^4 times higher than that from nova eruption. Therefore, σ_k of nova eruption should be very small. In short,

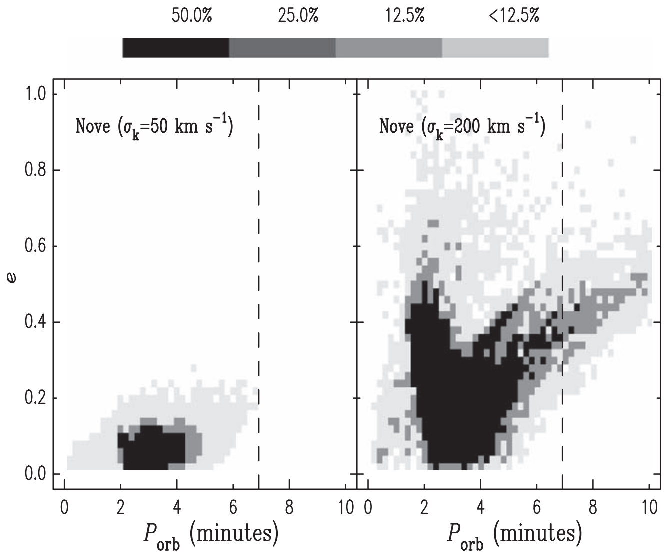

Figure 4. Distributions of the orbital periods and eccentricities for the CO + He WDs after nova eruptions with kick velocities of $\sigma_k = 50$ and 200 km s^{-1}, respectively. The dashed line gives the orbital period of ZTFJ1539.

the observational properties of ZTFJ1539 cannot likely be explained by a nova eruption.

3. Algol Scenario

An Algol system is a binary where the less massive donor fills its Roche lobe and transfers its matter to the more massive gainer, which does not fill its Roche lobe, and the former is the cooler, fainter, and older star, while the latter is still on the main sequence (Peters 2001). In the present paper, the Algol scenario means that the progenitor of ZTFJ1539 undergoes an Algol binary phase and the less massive WD forms earlier than the more massive WD.

3.1. Model of Binary Evolution

It is well known that the interactions of binary system produces many different types of astronomical phenomena. However, some involved physical processes are still openly debated, such as common envelope evolution (CEE). The importance of CEE in binary evolution is discussed in the literature (e.g., Ivanova et al. 2013). In general, the formation of a DWD system entails CEE once or twice (e.g., Postnov & Yungelson 2014). Unfortunately, it is extremely challenging to simulate a real CEE via both computation and analytic treatment. In the last section, using the BSE code, we obtained about 3.4×10^5 CO + He WDs via a population synthesis method. In the BSE code, the treatment of CEE is determined by the initial binding energy of the envelope and the initial orbital energy of two cores (details can be seen in Hurley et al. 2002). CEE is affected by two parameters: α_{CE} and λ. The former (α_{CE}) is the efficiency of the orbital energy used to expel the envelope (Paczynski 1976), and the latter (λ) is related to the structure of the donor (de Kool 1990; Xu & Li 2010). In fact, the outcome of CEE in the BSE code depends on the product of α_{CE} and λ (Hurley et al. 2002; Lü et al. 2006, 2012).

In the previous section, we used combining parameters $\lambda \times \alpha_{CE} = 1.0$ to calculate binary evolutions. Figure 5 shows the distribution of WD masses when He + CO WD systems form. Obviously, He + CO WD systems can be produced via

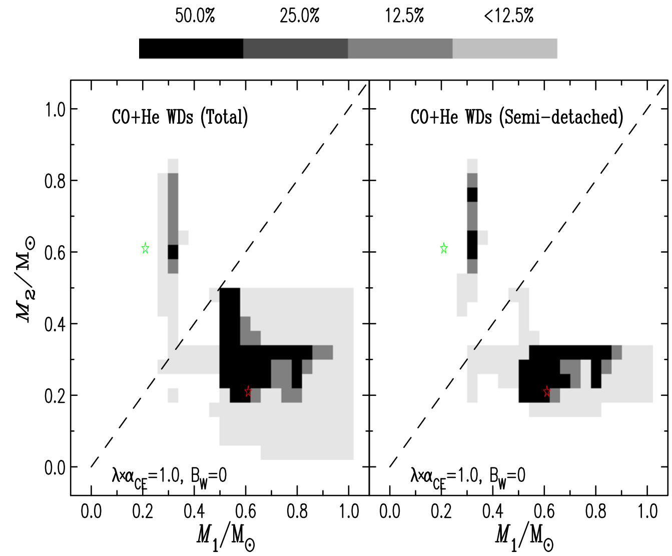

Figure 5. Distribution of WDs masses when He + CO WD systems form. The left panel represents all He + CO WD systems, while the right panel represents He + CO WD systems that can merge within Hubble time. The red star represents ZTFJ1539, where M_1 is the primary and M_2 is the secondary, that is, $M_1 = 0.61$ $M_\odot$ and $M_2 = 0.21$ $M_\odot$. However, the blue star represents ZTFJ1539, where $M_1 = 0.21$ $M_\odot$ and $M_2 = 0.61$ $M_\odot$. The dashed line indicates a position where $M_1 = M_2$. The He + CO WD systems positioned in the top left were produced via the Algol scenario.

the Algol scenario. These systems are shown in the top left of Figure 5. Unfortunately, the He WD masses of these systems are higher than about 0.25 $M_\odot$, while the mass of the ZTFJ1539 secondary is only 0.21 $M_\odot$. However, the products of binary systems are affected by many uncertain input parameters.

In order to efficiently produce Algol systems in RS CVn binaries, Tout & Eggleton (1988) suggested that the mass-loss rate of a giant star via stellar wind can be tidally enhanced by

$$\dot{M} = \dot{M}_R\left[1 + B_W \max\left(\frac{1}{2}, \frac{R}{R_L}\right)^6\right], \tag{3}$$

where $\dot{M}_R$ is the mass-loss rate from Reimers (1975), and R and R_L are the stellar and Roche-lobe radius, respectively. Here, B_W is an uncertain parameter. Compared with the observations, Tout & Eggleton (1988) took B_W as 10^4. As Figure 6 shows, the model with $B_W = 10^4$ can efficiently produce less massive He WD. However, this also results in a low orbital energy because the mass lost by stellar wind carries out the orbital angular momentum. Under the assumption of $\lambda \times \alpha_{CE} = 1.0$, the less massive He WD merges with its companion when this binary experiences CCE. Therefore, we take $\lambda \times \alpha_{CE} = 4$ so that the binary with a low-mass He WD can survive after a CCE. In the literature, the parameters λ and α_{CE} are assumed to be less than 1.0. However, λ and α_{CE} are very uncertain. Xu & Li (2010) calculated λ and found that its range changes from $\ll$0.5 to several tens, and even several hundreds. Simultaneously, other studies have also found α_{CE} to be larger than 1. For example, the default value of α_{CE} in the BSE code is 3 (Hurley et al. 2002).

Figure 6 illustrates different products for a binary with similar initial conditions under different assumptions: $\lambda \times \alpha_{CE} = 1.0$ and $B_W = 0$, or $\lambda \times \alpha_{CE} = 4$ and $B_W = 10^4$. As can be seen, a large

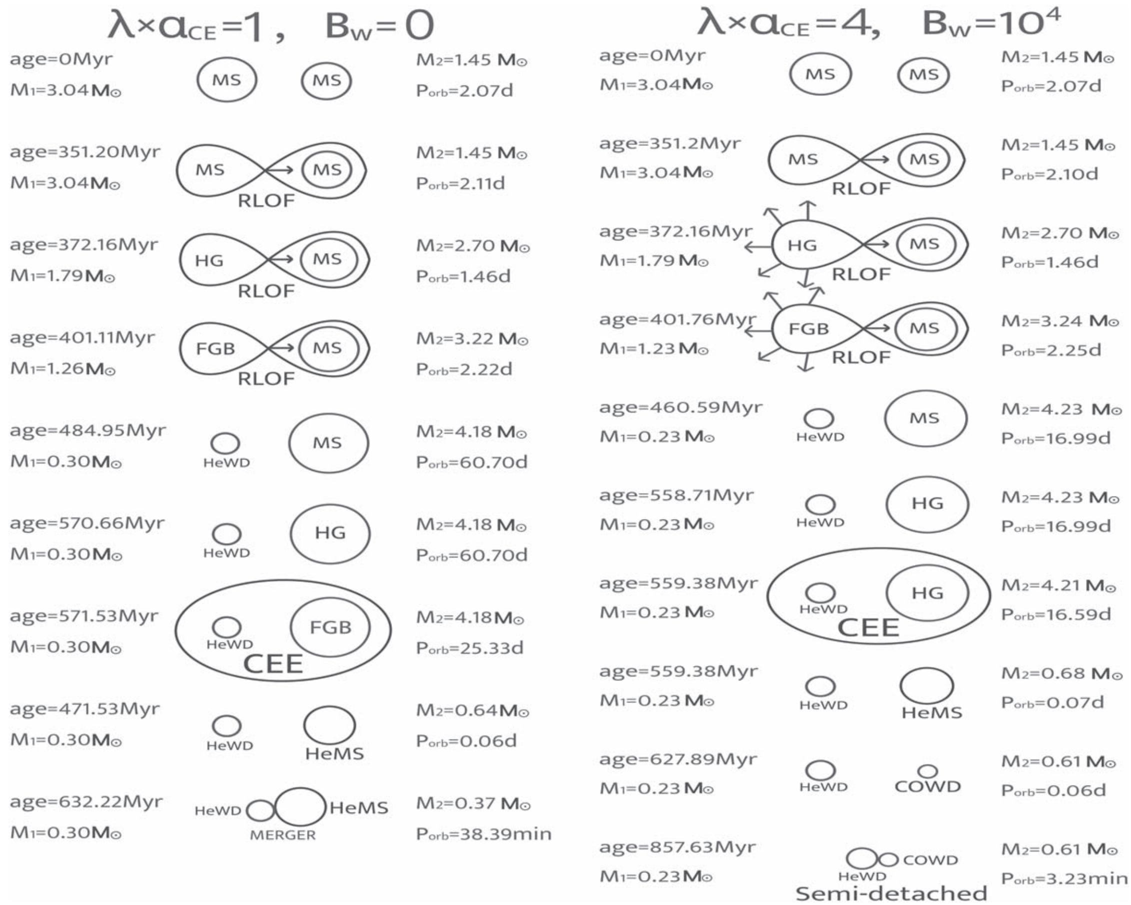

Figure 6. Evolutionary scenarios for binary systems with different input parameters. The left panel represents the model with assumptions of $\lambda \times \alpha_{\rm CE} = 1.0$ and $B_{\rm W} = 0$, while the right panel is for $\lambda \times \alpha_{\rm CE} = 4$ and $B_{\rm W} = 10^4$. MS, HG, FGB, HeMS, and RLOF mean main sequence, Hertzsprung gap, the first giant branch, helium main sequence, and Roche-lobe overflow, respectively. M_1, M_2, $P_{\rm orb}$, and age represent primary mass, secondary mass, orbital period, and the evolutionary time, respectively.

$B_{\rm W}$ can produce an He WD with lower mass, and a large $\lambda \times \alpha_{\rm CE}$ can ensure low-mass He WD survival during CEE.

3.2. Discussions

Figure 7 gives the results of He + CO WDs via the population synthesis method under assumptions of $\lambda \times \alpha_{\rm CE} = 4$ and $B_{\rm W} = 10^4$. The primary and secondary masses in ZTFJ1539 can be covered by He + CO WDs produced via the Algol scenario. However, we must mention that the results are sensitive to the values of the two parameters. If $B_{\rm W} < 10^3$, an He WD with a mass lower than about 0.27 $M_\odot$ hardly forms. If $\lambda \times \alpha_{\rm CE} < 2$, binary systems with low-mass He WD hardly survive during CEE.

Figure 8 shows the distributions of orbital period versus CO WD masses for He + CO WDs produced via the Algol scenario during different ages. Based on the temperature of the primary WD in ZTFJ1539, Burdge et al. (2019) estimated that its cooling age should be about 2.5 Myr. The top right panel in Figure 8 gives the distribution within 2.5 Myr after the formation of He + CO WDs. Our results cover the observations of ZTFJ1539, including the distribution when the cooling age is about 25 Myr. Therefore, it is possible in our binary model to produce ZTFJ1539.

In this work, through only changing the parameters $\lambda \times \alpha_{\rm CE}$ and $B_{\rm W}$, we have been able to explain the observational properties of ZTFJ1539 via the Algol scenario. In fact, there are

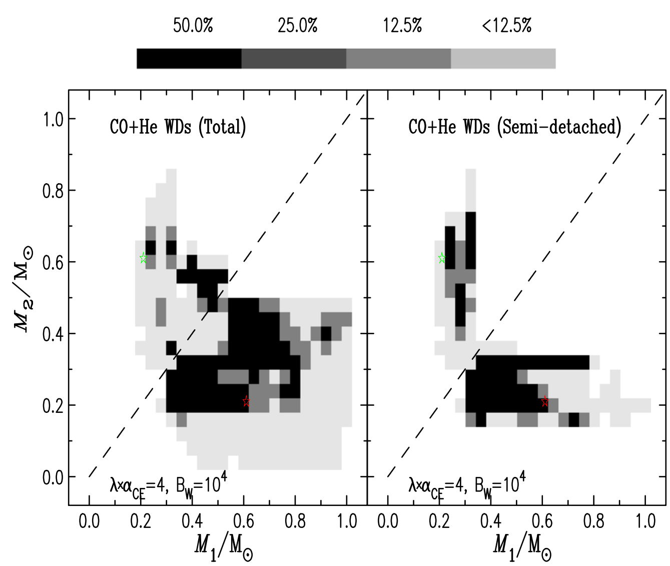

Figure 7. Same as Figure 5, but under assumptions of $\lambda \times \alpha_{\rm CE} = 4$ and $B_{\rm W} = 10^4$.

still other uncertain parameters that can affect binary evolution, such as mass-transfer rates and the efficiency of mass accretion during Roche-lobe overflow, rotation, the change in orbital angular momentum caused by mass loss from the binary system, stability criteria for mass transfer, and so on. AS more

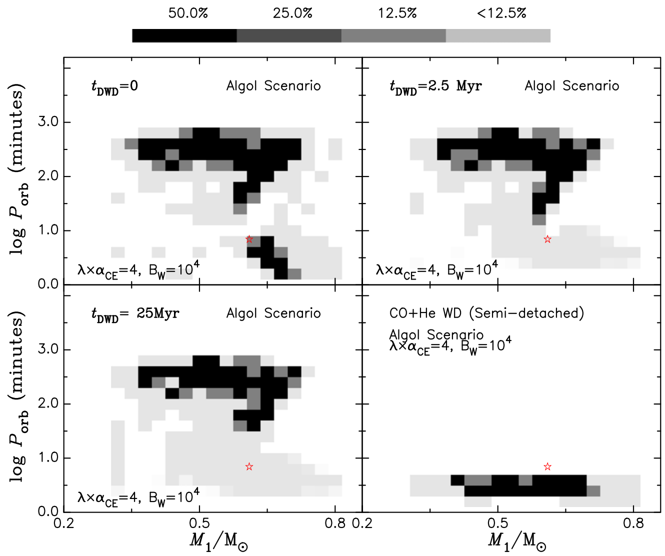

Figure 8. Evolution of orbital periods of He + CO WDs produced via the Algol scenario under assumptions of $\lambda \times \alpha_{\rm CE} = 4$ and $B_{\rm W} = 10^4$. $t_{\rm DWD}$ represents the lifetime of DWD formation.

DWDs like ZTFJ1539 are observed in the future, whether the Algol scenario can explain ZTFJ1539 will be determined. Simultaneously, these future observations will help restrain these uncertain parameters in the theoretical model for binary evolution.

4. Conclusions

In this work, we investigate the formation of ZTFJ1539 via nova and Algol scenarios. Assuming that the massive WD in ZTFJ1539 just experiences a thermal runaway, the nova scenario can explain the effective temperatures of the two ZTFJ1539 WDs. Unfortunately, in order to enlarge a semi-detached orbit of about 4–5 minutes to a detached orbit of about 7 minutes, the nova scenario needs a very high kick velocity of about 200 km s^{-1} during the nova eruption, which is comparable to the kick velocity of a CCSN. However, the energy released by CCSNe are about 10^4 times higher than that from nova eruptions. Simultaneously, this high kick velocity can result in a high eccentricity of about 0.2–0.6. There is no observational evidence for high eccentricity. Therefore, it is not likely that ZTFJ1539 was produced by the nova scenario. If the enhancement of the mass-loss rate of a giant star via stellar wind triggered by tidal effects and a high efficiency of ejecting CE are considered, the Algol scenario can also produce ZTFJ1539.

As a significant source of gravitational radiation close to the peak of *LISA*'s sensitivity, ZTFJ1539 has attracted our attention. Nevertheless, ZTFJ1539's progenitor and its outcome entail many unsolved physical processes of binary evolutions, such as CEE, mass loss, binary merger, and so on. ZTFJ1539 is worth further investigation.

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