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On the progenitors of type Ia supernovae

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The progenitors of type Ia supernovae (SNe Ia) are still under debate. There are two popular progenitor models for the formation of SNe Ia, i.e. the double-degenerate (DD) model and the single-degenerate (SD) model. However, none of these models can explain all of the observed properties of SNe Ia. In this paper, we introduce the white dwarf+helium (WD+He) subgiant channel in the context of the DD model and the semidetached WD+red-giant (RG) channel in the context of the SD model: (1) after considering the WD+He subgiant channel, the theoretical delay-time distribution of SNe Ia from the DD model can reproduce the observed results better; (2) by using an updated mass-transfer method for the semidetached WD+RG systems (varying with the local material states), the initial parameter space and SN Ia birthrate from the semidetached WD+RG channel is enlarged significantly.

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1. Introduction

Type Ia supernovae (SNe Ia) are good distance indicators in cosmology. They revealed the accelerating expansion of the Universe and led to the discovery of dark energy (e.g., Howell 2011). It is generally believed that SNe Ia result from the thermonuclear explosions of carbon-oxygen white dwarfs (CO WDs) in close binaries (e.g., Hoyle & Fowler 1960; Nomoto et al. 1984). However, the identity of the mass donor for the exploding CO WD is still not fully confirmed.

There are two most popular progenitor models for SNe Ia, i.e. the single-degenerate (SD) model and the double-degenerate (DD) model. In the SD model, the WD accretes H-rich or He-rich material from a non-degenerate companion, which can be a main-sequence, a red-giant, an asymptotic giant branch star or a Helium star via Roche-lobe overflow or wind-accretion process. In this case, the accreted material burns stably on the surface of CO WD, leading to the increase of the WD mass. When the WD mass approaches to the Chandrasekhar mass limit, it is supposed to explode as an SN Ia (e.g. Whelan & Iben 1973; Nomoto et al. 1984; Li & van den Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004; Wang et al. 2009). In the DD model, the mass donor of the exploding WD is another CO WD. Two WDs get close and close and eventually merge due to the gravitational wave radiation. If the total mass of the double WDs are larger than the Chandrasekhar mass limit, it is supposed that the primary WD will explode as an SN Ia (e.g. Iben & Tutukov 1984; Webbink 1984; Han 1998; Nelemans et al. 2001; Toonen et al. 2012). In addition, some other progenitor models have been proposed to explain the observed diversity of SNe Ia, e.g., the double-detonation model, the core-degenerate model, the collisional WD model, the single star model, the WDs near black hole model, etc (for recent reviews see Wang 2018; Soker et al. 2018; Livio & Mazzali 2018; Chen et al. 2024).

Recently, many efforts have been done on constraining the progenitors of SNe Ia, like SN Ia birthrates, delay time distributions, progenitor candidates, surviving companions, interaction between SN ejecta and companion and between SN ejecta and circumstellar material, early excess emission, late-time spectra and photometry, polarization properties, SN remnants, and so on. However, none of the proposed progenitor models can explain all of the observed properties of SNe Ia till now (e.g. Liu et al. 2023).

In this paper, we will introduce two channels: (1) in order to reproduce the observed delay-time distribution, we studied the WD+He subgiant channel in the context of the DD model; (2) in order to provide larger initial parameter space and birthrate, we studied the semidetached WD+red-giant (RG) channel in the context of the SD model by using an updated mass-transfer method.

2. The WD+He subgiant channel in the context of the double-degenerate model

In the DD model, the mass donor is usually assumed to be another CO WD, in which the merger of the double WDs driven by the gravitational wave radiation may produce SNe Ia (e.g., Iben & Tutukov 1984; Webbink 1984). Some observational and theoretical studies slightly favor the DD model (e.g. Howell et al. 2006; Yoon Podsiadlowski & Rosswog 2007; Hichen et al. 2007; Scalzo et al. 2010; Horesh et al. 2012; Graham et al. 2015). Especially, the DD model have the advantage of explaining the Galactic birthrates and delay time distributions of SNe Ia (e.g. Han 1998; Nelemans et al. 2001; Ruiter, Belczynski & Fryer 2009; Maoz, Mannucci & Nelemans

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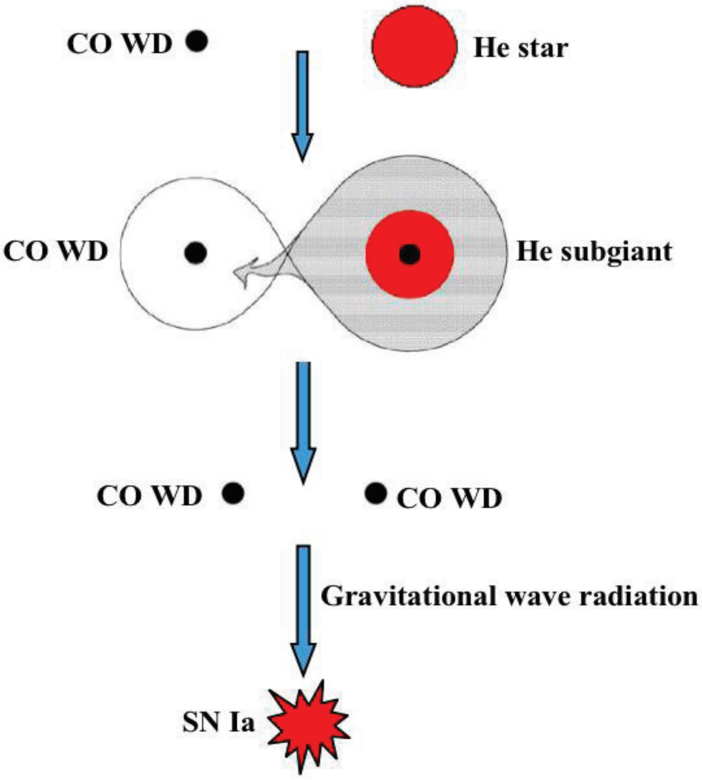

Figure 1: A cartoon for the WD+He subgiant channel for producing SNe Ia in the context of the DD model.

2014; Yungelson & Kuranov 2017); the delay times of SNe Ia here are defined as the time interval from the star formation to the thermonuclear explosion. However, the DTDs predicted by previous theoretical studies based on the DD model still have deficit with the observed SNe Ia at the early epochs of <1 Gyr and old epochs of >8 Gyr (e.g. Yungelson & Kuranov 2017).

It has been recently proposed that WD+He star systems would evolve to form double WD systems, and then produce SNe Ia when double WDs merge (see Ruiter et al. 2013; Liu et al. 2016; Liu, Wang, & Han 2018). In this channel, the He star fills its Roche lobe at the He subgiant stage, and transfers He-rich material to the primary WD. During this process, the mass of the primary WD would increase. When the He-rich shell in the He subgiant is exhausted, the binary becomes a double WD system, the merging of which potentially produce SN Ia explosion (Fig. 1). In Fig. 2, we provided the parameter space of WD+He star systems that would evolve to double WDs and then merge to produce SNe Ia in the $\log P^{\rm i} - M_2^{\rm i}$ plane, in which the initial WD mass $M_{\rm WD}^{\rm i}$ varies from 0.5 to $1.2\,{\rm M}_{\odot}$ for different contours. From this figure, we can see that the contours turn to move to upstairs for lower initial WD masses, which is caused by the requirement that the total mass of double WDs should be larger than the Chandrasekhar limit for producing SNe Ia. In recent observations, KPD 1930+2752, HD 265435 and Lan 11 are three WD+hot subdwarf systems that are progenitor candidates for SNe Ia based on this channel (see Fig. 2; Geier et al. 2007; Pelisoli et al. 2021; Luo et al. in preparation). More candidates are still needed in order to improve our understanding on this channel.

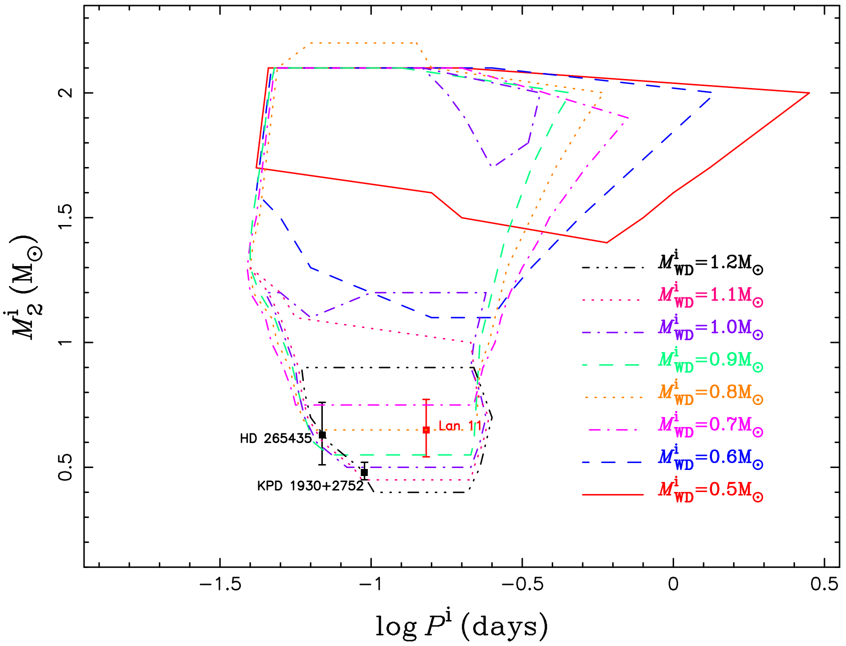

Figure 2: Parameter space of WD+He star systems for producing SNe Ia via the DD model. From Liu et al. (2018).

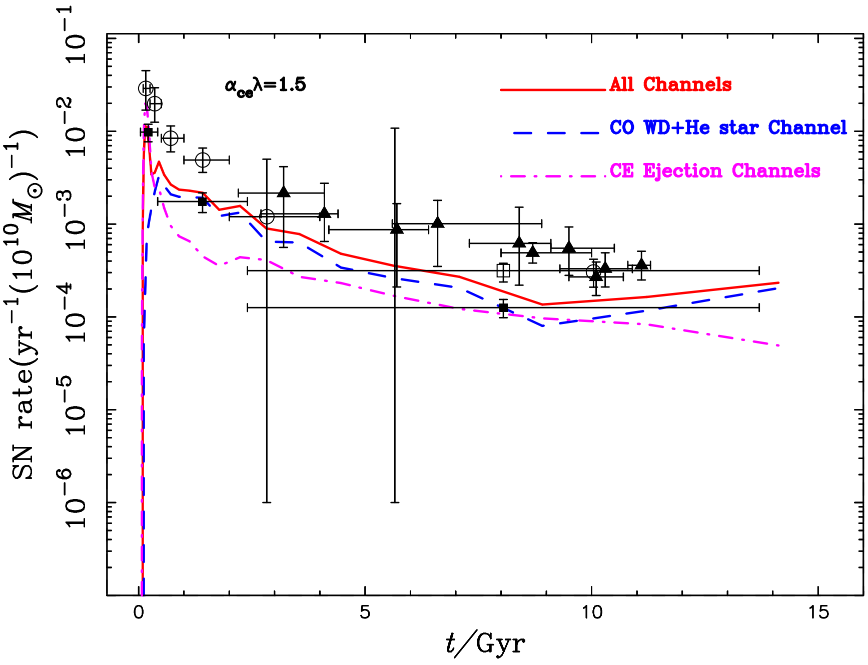

Figure 3: The theoretical DTDs of SNe Ia based on the DD model. Points with error bars represent the observational date of elliptical galaxies from the Subaru/XMM−Newton Deep Survey (the open circles; Totani et al. 2008), galaxy clusters at the redshifts from Z = 0 to Z = 1.45 (the filled triangles; Maoz, Keren & Avishay 2010), a galaxy sample from SDSS (the filled squares; Maoz, Mannucci & Timothy 2012), and an SN Ia sample from the Cluster Lensing And Supernova survey with Hubble (the open square; Graur & Maoz 2013).

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We presents the theoretical DTDs of SNe Ia from the merging of double WDs originating from different channels in Fig. 3. The delay times of SNe Ia range from 110 Myr to the Hubble time based on the WD+He subgiant channel, and from 70 Myr to the Hubble time based on all channels. The cut-offs at the large end of DTDs are artificial since the system ages have already reached the Hubble time. For SNe Ia from all channels, the DTDs are roughly proportional to t^{-1} and the rate of SNe Ia is comparable with that in the elliptical galaxies (or galaxy clusters) from observations. Similar to previous studies (e.g. Yungelson & Kuranov 2017), the CE ejection channels still have deficit compared with observations for SNe Ia in early and old epochs. After considering the WD+He subgiant channel, we found that the DTDs here can match better with the observations.

3. The semidetached WD+RG channel

In the SD model, the primary WDs can accrete H-rich matter from red-giant (RG) stars and form SNe Ia when they grow close to the Chandrasekhar mass limit, known as the symbiotic channel (e.g., Whelan & Iben 1973; Hachisu et al. 1996; Lv et al. 2009; Chen et al. 2011). Although the actual number of symbiotic stars in the Galaxy is still unknown (e.g., Mikołajewska 2012; Rodríguez-Flores et al. 2014), many symbiotic systems have been observed (e.g., Belczynski et al. 2000; Miszalski & Mikołajewska 2014), in which T CrB, RS Oph, V745 Sco and V3890 Sgr are possible progenitor candidates for SNe Ia (Kraft 1958; Brandi et al. 2009; Orlando et al. 2017; Mikołajewska et al. 2021). Furthermore, Patat et al. (2007) detected Na I absorption lines with low expansion velocities in SN 2006X, and speculated that the companion of the exploding WD may be an early RG star. However, prior studies have suggested that the birthrate of SNe Ia from the symbiotic channel is relatively low, significantly less than 1%. (e.g., Li & van den Heuvel 1997; Han & Podsiadlowski 2004).

A possible reason for this contradiction is that the mass-transfer prescription adopted previously is not suitable for RG binaries. The local gas density and sound velocity in the region around the inner Lagrange point L_1 of a RG star are significantly lower than that in a MS star. Lubow & Shu (1975) proposed that the mass-transfer process can be investigated by integrating the local gas density and sound velocity over the plane that is perpendicular to the line of centres connecting the two stars, and passing through the inner Lagrangian point. By assuming that the equation of state of stars obey an adiabatic power-law, and that the mass outflow is laminar and occurs along equipotential surfaces, Ge et al. (2010) obtained an approximated prescription for the mass-transfer process. In this prescription, $\dot{M}_2$ is a function of local material states.

We used the updated mass-transfer prescription to evolve a large number of semidetached WD+RG systems to provide the initial parameter space for the production of SNe Ia. The parameter space of WD+RG systems that can produce SNe Ia is increased significantly judging by our calculations (Fig. 4). The upper panel of Fig. 4 shows that the grid from the present work has larger initial donor masses and shorter initial orbital periods. In these regions, $\dot{M}_2$ would be so high that the binary enters a CE process or strong optically thick wind process in the model of Li & van den Heuvel (1997), preventing them from forming SNe Ia. The lower panel presents the initial parameter space for the production of SNe Ia, and the final regions of WD+RG systems at the moment of SN Ia explosions in the orbital period-secondary mass ($\log P - M_2$) plane, in which $M^{\rm i}_{\rm WD} = 1.0, 1.1$ and $1.2\,M_\odot$. We found that $M^{\rm i}_{\rm WD} = 1.0\,M_\odot$ is the minimum initial WD mass for

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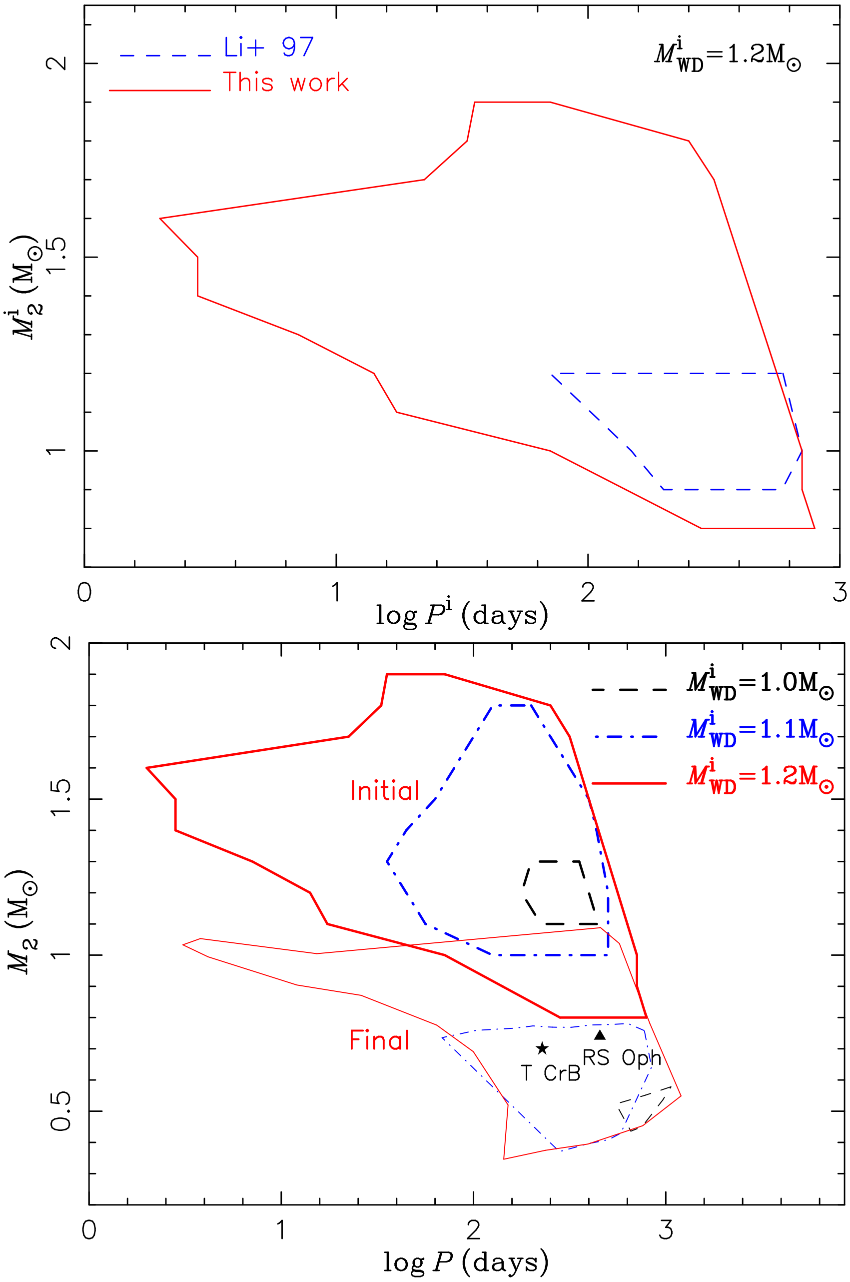

Figure 4: Parameter space of semidetached WD+RG star systems for producing SNe Ia via the SD model. From Liu et al. (2019).

producing SNe Ia as its region almost vanishes. We also found that the symbiotic systems RS Oph and T CrB could form SNe Ia via the symbiotic channel (for more details see Sect. 4). This channel could produce SNe Ia with intermediate and old ages, contributing up to 5% of all SNe Ia in the Galaxy. Our model increases the SN Ia rate from this channel by a factor of 5 (see Liu et al. 2019).

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4. Summary

In this paper, we reviewed some recent works on two formation channels for SNe Ia, i.e. the WD+He subgiant channel in the context of the DD model and the semidetached WD+RG channel in the context of the SD model. After considering the WD+He subgiant channel, we found that the observed delay-time distribution of SNe Ia can be better reproduced based on the DD model. By using an updated mass-transfer method for semidetached WD+RG systems, the initial parameter space and birthrate for SNe Ia are significantly increased. Up to now, there are still many unresolved questions on the SN Ia progenitors. Further the observational and theoretical studies on the progenitors of SNe Ia are required.

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