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Binary population synthesis for the core-degenerate scenario of SN Ia progenitors

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Abstract. The core-degenerate (CD) scenario has been proposed as an alternative way for the production of type Ia supernovae (SNe Ia). In this scenario, SNe Ia are formed at the final stage of common-envelope evolution from a merger of a carbon-oxygen white dwarf (CO WD) with the CO core of an asymptotic giant branch companion. However, the birthrates of SNe Ia from this scenario are still not well determined. In this work, we performed a detailed investigation on the CD scenario based on a binary population synthesis (BPS) approach. The SN Ia delay times for this scenario are mainly in the range of $\sim$90 Myr$-$2200 Myr, contributing to the observed SNe Ia with short and intermediate delay times. The Galactic birthrates of SNe Ia from this scenario range from $\sim 4.6\times10^{-5}\mathrm{yr}^{-1}$ to $\sim 4.3\times10^{-4}\mathrm{yr}^{-1}$, accounting for $\sim$2$-$14% of total SNe Ia. Especially, SNe Ia with circumstellar material from this scenario contribute to $\sim$1$-$10% of total SNe Ia, which means that the CD scenario can reproduce the observed birthrates of SNe Ia like PTF 11kx.

Key words. stars: evolution – binaries: close – supernovae: general – white dwarfs

1. Introduction

Type Ia supernovae (SNe Ia) are among the most powerful explosions in the Universe and have high scientific values in Cosmology. It has been suggested that SNe Ia arise from thermonuclear explosions of carbon-oxygen white dwarfs (CO WDs) in binaries, although their progenitor systems are still under debate. Over the past four decades, two main families of SN Ia progenitor scenarios have been discussed frequently, that is, the single-degenerate scenario and the double-degenerate scenario (e.g. Han & Podsiadlowski 2004; Wang et al. 2009, 2010, 2014; Toonen et al. 2012, 2014). Some variants of these two progenitor scenarios are needed to explain the observed diversity of SNe Ia (e.g. Wang & Han 2012; Maoz et al. 2014).

Most simulations for the double-degenerate scenario relate to the merger of two cold CO WDs. However, a CO WD can also merge with the hot CO core of an asymptotic giant branch (AGB) star, and then produce an SN Ia, which is known as the core-degenerate (CD) scenario (e.g. Soker 2013). In the CD scenario, an SN Ia explosion might occur shortly or a long time after the common envelope (CE) stage. Although this scenario may explain some properties of SN Ia diversity, SN Ia birthrates from this scenario are still not well determined (e.g. Ilkov & Soker 2013). Ilkov & Soker (2013) argued that this scenario can reproduce the observed birthrates of total SNe Ia based on a simplified binary population synthesis (BPS) code.

The purpose of this article is to investigate SN Ia birthrates and delay times for the CD scenario using a detailed Monte Carlo BPS approach. We describe the numerical methods and assumptions for the BPS approach in Sect. 2, and give the BPS results in Sect. 3. Finally, a discussion and summary is presented in Sect. 4.

2. Numerical methods

In the CD scenario, a Chandrasekhar or super-Chandrasekhar mass WD could be formed through the merger of a cold CO WD with the hot CO core of an AGB star. A series of Monte Carlo BPS simulations for the CD scenario are performed. We adopted the following assumptions as the criteria for producing SNe Ia through the CD scenario (e.g. Soker 2013):

(1) The combined mass of the CO WD ($M_{\rm WD}$, primary) and the AGB core ($M_{\rm core}$, secondary) during the final stage of CE evolution is larger than or equal to the Chandrasekhar limit.
(2) The WD and the AGB core merge during the final stage of CE evolution.
(3) In order to avoid the formation of ONe WDs that cannot produce SNe Ia, both $M_{\rm WD}$ and $M_{\rm core}$ are limited to be $<1.1\,M_{\odot}$.

The CO WD is usually disrupted and accreted onto the more massive AGB core during the merging process. However, in some conditions the AGB core would be disrupted and accreted onto the cooler CO WD if $M_{\rm WD} > M_{\rm core}$. In such case, the SN explosion may occur shortly after the CE stage, resulting in an SN Ia inside a planetary nebula shell, which may reproduce the properties of some SNe Ia with circumstellar material such as PTF 11kx (Soker et al. 2013). This case is known as the violent prompt merger scenario (e.g. Soker et al. 2013), which is studied in the present work.

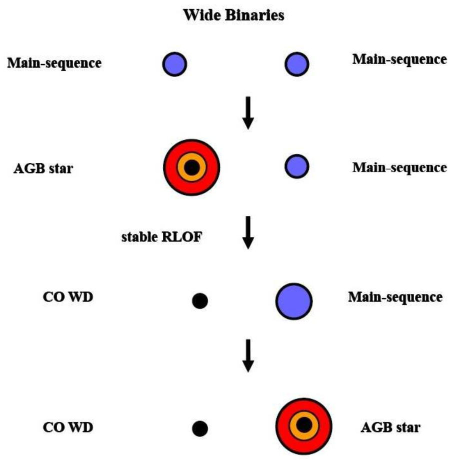

Fig. 1. Binary evolutionary way to WD+AGB systems.

We carried out a series of Monte Carlo BPS simulations for the CD scenario. In each simulation, we followed the evolution of 1×10^7 primordial binaries from star formation to the formation of WD+AGB systems using the Hurley binary evolution code (Hurley et al. 2002). In the CD scenario, the merger of WD+AGB core originates from the CE evolution. In oder to obtain the output of the CE stage, the standard energy equation is adopted. Here, we consider several different values (e.g. 0.2, 0.3 and 0.5) of the CE ejection efficiency $\alpha_{\rm CE}$ to examine its influence on the final results.

In Fig. 1, we present the binary evolutionary way to form WD+AGB systems. The primordial primary first fills its Roche lobe when it evolves to the AGB stage (it now contains a CO core in its center). Note that the primary loses a lot of matter through the stellar wind before it fills its Roche-lobe. At the end of the Roche-lobe overflow (RLOF), the primary becomes a CO WD. Meanwhile, the MS secondary becomes a massive star due to the stable mass transfer, resulting in the formation of a CO WD+MS system. The CO WD+MS system continues to evolve, and the MS secondary may fill its Roche-lobe again when it

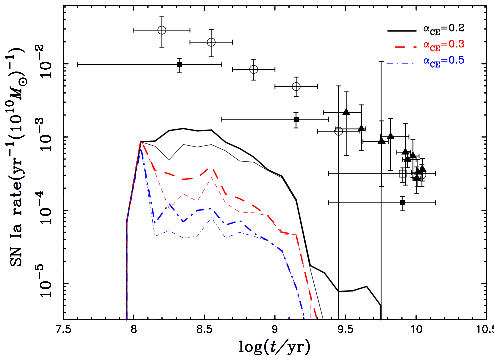

Fig. 2. Delay-time distributions of SNe Ia based on a single starburst of 10^{10} $M_\odot$. The thick lines are for all SNe Ia from the CD scenario, whereas the thin lines are only for SNe Ia with circumstellar material like PTF 11kx. The open circles are taken from Totani et al. (2008), the open square is from Graur & Maoz (2013), the filled triangles and squares are from Maoz et al. (2010, 2012).

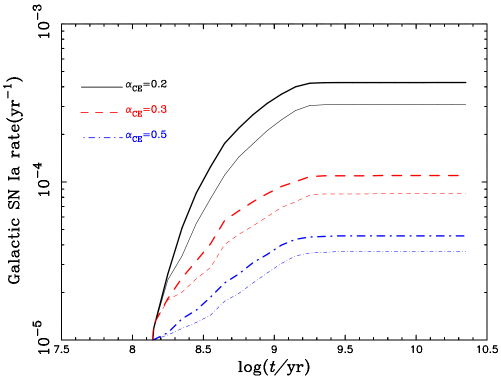

Fig. 3. Similar to Fig. 2, but for the evolution of the Galactic SN Ia birthrates with time for a constant Population I SFR with different values of α_{CE}.

evolves to the AGB stage. At this stage, a CE may be formed due to the dynamically unstable mass transfer, resulting from the deep convective envelope of the AGB star and the large mass ratio. The CO WD will merge with the CO core of the AGB star during the CE stage if the CE cannot be ejected. Finally, an SN Ia may be produced through the CD scenario.

For the CD scenario, SN Ia explosions for the ranges of the initial mass of the primordial primary ~2.0-6.3 $M_\odot$, and the initial mass of the primordial secondary ~1.5−6.0 $M_\odot$. The initial orbital period of the primordial system needs to be wide enough (e.g. >8 yr) for the primordial primary that can evolve to an AGB star.

3. Results

In the CD scenario, the theoretical delay times of SNe Ia are the sum of the evolutionary timescale from primordial binaries to the formation of CD systems and the spin-down timescale from the merger product of WD+AGB core to SN explosion. In Fig. 2, we present the SN Ia delay time distributions for the CD scenario based on a single starburst of $10^{10} M_\odot$, where the spin-down time is included in the delay time. The estimated delay times for this scenario are mainly in the range of ~90 Myr−2200 Myr after the starburst, which may have a contribution to the SNe Ia with short and intermediate delay times.

In Fig. 3, we show the evolution of the Galactic SN Ia birthrates with time for the CD scenario by adopting metallicity Z=0.02 and a constant SFR of 5 $M_\odot$yr^{-1}. The theoretical birthrates from this scenario are in the range of ~4.6×10^{-5}yr^{-1}−4.3×10^{-4}yr^{-1}, accounting for ~2−14% of the observations. The SN Ia birthrates from the CD scenario are lower than those from observations, which means that the CD scenario can only form a small part of total SNe Ia. We note that the birthrates of SNe Ia from the CD scenario increase for a low value of α_{CE}. This is because a low value of α_{CE} leads to shorter orbital separation, resulting in more mergers of WD+AGB core.

Soker et al. (2013) recently suggested that the violent prompt merger in the CD scenario may account for the very massive circumstellar material in PTF 11kx, and for the presence of hydrogen shells in the circumstellar material. According to our BPS simulations, the Galactic birthrates for SNe Ia with circumstellar material are in the range of ~3.6×10^{-5}yr^{-1}−3.1×10^{-4}yr^{-1}, accounting for ~1−10% of total SNe Ia, which can reproduce the birthrates of SNe Ia like PTF 11kx; the observed fraction of SNe Ia with circumstellar material is estimated to be ~0.1−1% (e.g. Dilday et al. 2012).

4. Discussion and summary

According to a simple BPS code, Ilkov & Soker (2013) suggested that the CD scenario can reproduce the observed birthrates of SNe Ia, and claimed that this scenario plays an important role for producing SNe Ia. However, we found that this scenario can only account for a small fraction (~2−14%) of SNe Ia based on our detailed BPS approach. The main difference between these two works is the treatment of the binary interaction during mass transfer. Ilkov & Soker (2013) obtained the new mass of the primordial secondary after the primordial primary passed through the AGB stage and became a WD (with mass $M_{\rm WD}$) as $M_{\rm 2new} = M_2+\eta(M_1-M_{\rm WD})$, where η is the mass transfer parameter, M_1 and M_2 are the initial masses of the primordial primary and secondary, respectively. The value of the mass transfer parameter η in our work is in the range of ~0.3−0.45 that is only half of the value (η~0.8−0.9) taken by Ilkon & Soker (2013); the high mass transfer parameter leads to the formation of more massive AGB stars and larger CO cores, and thus gives a much higher birthrates of SNe Ia.

Soker et al. (2013) recently suggested that the violent prompt merger in the CD scenario may explain some SNe Ia with very massive circumstellar material such as PTF 11kx. If we adopted a strict assumption on the mass of the WD+AGB core and the envelope mass ($M_{\rm env}$) of the AGB star (e.g. $M_{\rm WD}$ + $M_{\rm core} \geq 1.8M_{\odot}$ and $M_{\rm env} \geq 0.5M_{\odot}$; Soker et al. 2013), the SN Ia birthrates from the violent prompt merger scenario will decrease to $\sim1.4\times10^{-5}{\rm yr}^{-1}-5.6\times10^{-5}{\rm yr}^{-1}$, accounting for ~0.4−2% of all SNe Ia, which can still reproduce the observational number of SNe Ia like PTF 11kx.

By employing a detailed BPS approach, we got an upper limit for the birthrates of SNe Ia based on the CD scenario (no more than 14% of total SNe Ia). The birthrates in this simulation are lower than those in Ilkov & Soker (2013), the main reason of which is that we adopted a detailed mass-transfer process. We found that SNe Ia from the CD scenario may mainly contribute to the SNe Ia with short and intermediate delay times although this scenario may also produce a few SNe Ia with long delay times. The birthrates of SNe Ia with circumstellar material are estimated to be ~1−10% of total SNe Ia, which can match the observed number of SNe Ia like PTF 11kx. In order to put further constraints on the CD scenario, more numerical simulations and observational evidence for this scenario are needed.

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